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The structure of the Central-Eastern External Rif (Morocco); Poly-phased deformation and role of the under-thrusting of the North-West African paleo-margin

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ABSTRACT

The Rif belt (Northern Morocco) forms the western edge of the Alpine-Himalayan orogenic system, resulting from the progressive closure of the Tethys oceanic domain between the Africa and Eurasia plates. The External Rif, topic of this paper, comprises three paleogeographic zones, namely the Prerif, Mesorif and Intrarif, inherited from the zonation of the North-West African paleo-margin from proximal to distal domains, respectively. Its current architecture displays tectonic windows (belonging to the Mesorif) at depth supporting far-travelled thrust-sheets (namely, the Senhadja and Higher Nappes of Mesorif and Intrarif origin, respectively). A puzzling aspect of the Mesorif structure is the coexistence of metamorphic and non-metamorphic units within the tectonic windows and Senhadja Nappes. In particular, the latter presents a chaotic structure, which origin remains under debate. We integrate previous studies and new data (field observations, geological mapping and thermochronology results) to reassess the structure of the External Rif and propose an up-dated interpretation of its Cenozoic evolution. In the Prerif and Mesorif, we highlight a poly-phased tectonic evolution occurring before and after a major unconformity (the "Mesorif Unconformity"). This unconformity seals a pre-Miocene compressional event that we relate to the under-thrusting of the North-African paleo-margin below the Maghrebian Tethys (the former Tethys branch located between South Iberia and North Africa). The MP-LT metamorphism, recorded in the metamorphic tectonic window of the Temsamane Massif, is a direct vestige of this process. After the "Mesorif Unconformity", i.e. during the Miocene, the regional geodynamics is ruled by the westward translation of the Alboran Domain and the coeval out-of-sequence deformation of the "oceanic" units in front of it (Flyschs and Intrarif Units, the most internal parts of the External Rif). This process directly results from the subduction of the Maghrebian Tethys below the Alboran Domain. The docking of the Intrarif Units against the already exhumed Temsamane Units and Senhadja Nappes generated an uplift and the subsequent detachment of the top of the Intrarif lithostratigraphic pile, forming the Higher Nappes. We show that the chaotic structure of the Senhadja Nappes is only apparent, being mostly inherited from the Mesozoic rifting. Results of apatite fission track, apatite helium dating and thermal modelling from the gabbroic intrusions of the Senhadja Nappes confirm an overburden by the Higher Nappes and their subsequent exhumation during the Upper Miocene. Finally, all these elements are integrated in a coherent model incorporating the External Rif in the geodynamics of the West Mediterranean.

Keywords: North-West African paleo-margin under-thrusting; External Rif structure; Senhadja Nappe Thermochronology

1- Introduction

The Rif belt in Northern Morocco belongs to the western peri-Mediterranean termination of the Alpine-Himalayan orogenic system (Durand-Delga et al., 1960-62; Wildi, 1983; Frizon de Lamotte et al., 1991; Lonergan and White, 1997; Platt et al., 2013) (Fig. 1). Together with the Betic Cordilleras in Southern Spain, it forms the Gibraltar Arc and marks the transition from the Atlantic to the Tethys realms (Ricou, 1994).

As for other orogenic belts, the Rif belt is divided into internal and external zones, characterized by distinct paleogeography, deformation style and metamorphic imprints. The internal Rif metamorphic complexes, including the Beni-Bousera peridotite massif, have been extensively investigated in recent years (Frets et al., 2014; Gueydan et al., 2015; Rossetti et al., 2020). Conversely, the External Rif has globally been less investigated; recent studies specifically focused on the following questions:

-The structure, deformation history and metamorphic imprint of the Temsamane Massif (Negro et al., 2007, 2008; Booth-Rea et al., 2012; Jabaloy-Sánchez et al., 2015; Azdimousa et al., 2019a and b);
- The Mesozoic evolution of the North African rifted margin (Michard et al., 2018; Gimeno-Vives et al., 2019; 2020);
- The recent tectonic-paleogeographic evolution in relation with the Messinian salinity crisis (Capella et al., 2017; Capella et al., 2018);
- The active tectonics and, in particular, its relationships with the Mw 6.3 Al Hoceima (2004) earthquake (d'Acremont et al., 2014; Galindo-Zaldívar et al., 2015).

Thus, numerous unsolved questions remain on the general structure and orogenic evolution of the External Rif.

As part of the Tell-Rif orogenic system, the Rif is basically composed of tectonic windows, divided into metamorphic and non-metamorphic ones, supporting large thrust sheets, made of Late Cretaceous-Paleogene detached cover (see a review in Leprêtre et al., 2018). The metamorphic windows constitute a specificity of this orogenic system, namely the "External Metamorphic Massifs" (EMMs), scattered along the Mediterranean shoreline (Fig. 1), the widest and most emblematic example being the Temsamane Massif in the Eastern Rif (Frizon de Lamotte, 1985; Frizon de Lamotte, 1987a; Negro et al., 2007; Jabaloy-Sánchez et al., 2015). The other tectonic windows, less studied in general, are free of significant metamorphic imprint but show evidence of poly-phased contractional deformation (in the Rif: Andrieux, 1971; Leblanc 1979; in the Tell: Fenet et al., 1969; Leprêtre et al., 2018). Currently, no consensus exists about

the structural position nor the geodynamic significance of the EMMs while their coexistence with non-metamorphic tectonic windows is not solved either.

The thrust sheets (nappes) documented across the External Rif record also a more complex history compared to the rest of the Tell-Rif system. Below large Late Cretaceous-Paleogene thrust sheets, the Senhadja Nappes offers a puzzling duality between metamorphic and non-metamorphic units questioning their initial location and evolution (Durand-Delga, 1960-62) (Fig.2).

Therefore, this paper aims to provide an integrative and comprehensive overview of the Cenozoic history of the External Rif and of its integration at regional scale. More specifically, we clear up the structural and chronological relationships between the different units derived from the former North-African margin (Favre et al., 1991; Michard et al., 2018; 2020; Gimeno-Vives et al., 2019; 2020). New field observations combined with the critical review of existing literature, allow us to provide an updated overview of the different units illustrated by a new harmonized structural map and three new regional cross-sections of the Central-Eastern External Rif. New thermochronological results, together with a reassessment of existing geochronological data, help us to better characterize the Cenozoic tectonic timetable. Finally, we propose a reinterpretation of the tectonic evolution of the External Rif since the onset of convergence between Africa and Eurasia, discussing the timing of emplacement of the main structural units during the Cenozoic. Especially, three major points are addressed and discussed:

- The repartition and significance of the pre-Miocene contractional deformation;
- The integration of the metamorphism observed in the Eastern Rif in a geodynamic scenario at the scale of North-West Africa;
-The origin and transport mechanisms of the large thrust-sheets, emplaced during the Middle-Upper Miocene;

2. Architecture and Miocene geodynamics of the Rif belt

2.1 The general architecture of the Rif belt

The Rif shares its tectonic zonation with the Western Tell and, partially, with the western part of the Betics through a large orogenic orocline known as the Gibraltar Arc (Durand-Delga and Fontboté, 1980; Platt et al., 2003; Fig. 1). However, the External Betics and the External Rif Zones are derived from the inversion of two distinct paleogeographic domains, the South-

Iberian (García-Hernández et al., 1980; De Ruig, 1992; Vera et al., 2004; Escosa et al., 2018) and the North African paleo-margins (review in Gimeno-Vives et al., 2019), respectively.

The Rif belt (Suter, 1980 a and b; Chalouan et al., 2008), belonging to the Tell-Rif (or Maghrebides), is composed of three major paleogeographic-tectonic domains: the Internal Domain, the Flyschs Domain and the External Domain (Fig. 1). They correspond to two distinct continental domains bounding a former deep basin, of likely oceanic nature, the so-called "Bassin des Flyschs" or "Maghrebian Tethys" (Durand-Delga and Fontboté, 1980; Wildi, 1983; Bouillin et al., 1986; Guerrera et al., 2012; Leprêtre et al., 2018):

- The Internal Domain or Alboran Domain is the "Al" of the "AlKaPeCa" (Alboran-Kabylie, Peloritan-Calabria) province (Bouillin et al., 1986; Bouillin, 1986), currently dispersed around the southern part of the West-Mediterranean (Fig. 1). The Alboran Domain corresponds to units deriving from the northern paleo-margin of the Maghrebian Tethys (i.e. east to south-east Iberian margin). It is composed of a tectonic stack of metamorphic terrains of Variscan and Alpine ages and a non-metamorphic Mesozoic cover, the so-called "Dorsale Calcaire" (Durand-Delga, 1969; Bouillin, 1986; Chalouan et al., 2008). This Domain includes also the extended basement located in the offshore Alboran basin (Fig. 1) (Comas et al., 1999; Do Couto et al., 2016), which developed from the Early Miocene onwards.

- The Flyschs Domain corresponds to a nappe stack composed by Upper Jurassic pelagic sediments followed upward by Cretaceous to Early Miocene (Burdigalian) turbiditic sequences, accumulated over a highly thinned continental and/or oceanic crust (i.e. the Maghrebian Tethys) (Durand-Delga et al., 1980; Bouillin, 1986; Guerrera et al., 2005; Luján et al., 2006; Zaghloul et al., 2010; Belayouni et al., 2013; Vitale et al., 2014). The continuity of the Flyschs Domain from the Western Betics to Sicily, and even the Apennines, is an important point showing that the Maghrebian Tethys was initially located south of the Alboran Domain and not north of it, as proposed by Vergés and Fernandez (2012) and Casciello et al. (2015).

- The External Domain (Fig. 2), over-thrusted by the Internal and Flysch Domains, represents the former North African margin (Favre et al., 1991; Favre, 1992; Michard et al., 2014; Gimeno-Vives et al., 2019). In the literature, it was firstly merged with the Flyschs Domain in a "*Zone Marno-Schisteuse*" (Fallot, 1937). Then, the Flyschs were recognized as independent nappes and the remaining "*Zone Marno-Schisteuse*" divided in two domains: the Rif *s.s.* and the Prerif (Durand-Delga et al., 1960-62). Finally, three paleogeographic-tectonic zones were distinguished, namely the Prerif, Mesorif and Intrarif (see the masterly map synthesis by Suter 1980 a and b) in which Gimeno-Vives et al. (2019) recognized the different domains of a magma-poor rifted margin. As a signature of their Cenozoic evolution, Prerif and Mesorif display a strong unconformity that

will be called hereafter the “Mesorif unconformity” well expressed in this domain. This unconformity does not exist in the Intrarif nor in the Flyschs Domain.

2.2 Miocene geodynamics of the Rif

The present-day architecture of the Rif belt results principally from top-to-the-west tectonic movements. The westward transport is active since the Miocene and related to the translation of the Alboran Domain, governing the geodynamics of the region. These Miocene movements are recognized and well-characterized at the scale of the whole Betic-Rif system (Frizon de Lamotte et al., 1991; Lonergan and White, 1997; Platt et al., 2013). As we detail below, these westward Miocene movements do not result from the overall convergence between the bounding plates but from the own dynamics of the subduction occurring in-between. It is the reason why the Rif can be considered as an archetype of “subduction orogen" (see a review in Royden and Faccenna, 2018).

At the scale of the Rif belt, the deformation is partitioned between two distinct structural trends in map view (Fig. 1): (1) A NW to NNW structural trend, accommodating the frontal westward thrust movement resulting from the Alboran migration, and a NE to ENE structural trend, related to left-lateral strike-slip movements accommodating the lateral displacement. The second trend is exemplified by two major fault-zones: the Jebha Fault Zone, limiting the Alboran to the Flyschs Domains and the Nekor Fault Zone, located between the Ketama Unit belonging to the Intrarif and the Mesorif units where we find the tectonic windows (Leblanc and Olivier, 1984) (Fig. 1). The junction of these trends explains the “corners” observed on the map (Fig. 1 b). A first corner is observed at the junction between the Alboran and Flyschs Domains closed to the city of Chefchaouene. A second corner, within the External Domain is close to the city of Taounate (Fig. 1).

As indicated above, the westward movements are well-characterized at the scale of the whole Betic-Rif system. Nevertheless, debates remain regarding the amount of displacement of the Alboran Domain, which can vary considerably from one model to another. Depending on the authors, the lateral translation of Alboran matches to dozens (Jolivet and Faccenna, 2000; Platt et al., 2003; Platt et al., 2013; Chertova et al., 2014; Crespo-Blanc et al., 2016) or hundreds of kilometers (Mauffret et al., 2004; Van Hinsbergen et al., 2014; Leprêtre et al., 2018). However, all studies agree that the westward movements are several times faster than the Africa-Iberia convergence emphasizing the major role of slab retreat in this orogeny (Wortel and Spakman, 2000; Mancilla et al., 2015). The slab retreat, resulting from the on-going delamination of the sub-continental African mantle (Perouse et al., 2010), is still active in the Rif system as demonstrated by GPS measurements (Perouse et al., 2010; Koulali et al., 2011; Nocquet, 2012;

Mancilla et al., 2013). These results show that the Nekor Fault Zone is acting as the current boundary between the moving Rif and stable Africa.

Thus, the Miocene geodynamics of the Rif, recorded in both the internal and external zones, is controlled by the subduction occurring in-between. An older and different history is recorded in the External Rif Domain. To understand its geodynamic significance, we have first to revisit the External Rif edifice.

3. The structure of the Central and Eastern External Rif revisited

To illustrate the structure of the External Rif, we will rely on a new tectonic map (Fig. 2) and three geological cross-sections (Fig. 3). Given the general kinematics of the Rif belt during the Miocene, the choice of the cross-sections trend is crucial to illustrate optimally the architecture of the Central and Eastern External Rif. At the scale of the orogenic system, the cross-sections should be parallel to the main movement (i.e. toward the SW to WSW) to exemplify the geometry and the kinematics of the key structures. Nevertheless, a major partitioning occurred along the Nekor Fault Zone acting as a lateral ramp. Therefore, contrasting with the main transport direction, the tectonic movement was roughly southwards in the regions situated south of the Nekor Fault Zone (Frizon de Lamotte et al., 1991). It was consequently strongly oblique or even perpendicular to the Nekor Fault Zone. Hence, looking at the N-S to NW-SE geological cross-sections presented below, the reader must keep in mind that the kinematics changes drastically north and south of the Nekor Fault Zone (Fig. 3). Given that this structure is inherited from the Mesozoic rifting stages (Gimeno-Vives et al., 2019), it is interesting to note that the cross-sections (Fig. 3) are perpendicular to the major extensional faults of the former margin. The different tectonic pieces constituting the External Rif are presented below from south to north (Fig. 3, 4).

3.1 The Foreland and the Prerif

The foreland of the Rif belt is shaped by three main domains from west to east: the Western Meseta Domain, the Atlas system and the Eastern foreland (Fig. 1). These three domains share the same Miocene cover, constituting the Rif foredeep basin. The Miocene sediments are overlaying the substratum, with a major sedimentary hiatus in-between, indicating a strong erosion, which occurred before the development of the foredeep.

In the Western Meseta Domain, the Variscan basement is widely exposed. The sediments of the Miocene foredeep are locally deposited directly on top of it, as shown in boreholes north of Rabat (Suter, 1980a) (Fig. 1 and 4). Laterally, the Miocene cover rests over the Mesozoic sequence, recording important thickness variations. These variations are related to an Upper

Triassic rifting phase associated with the development of NE trending grabens (i.e. the Khemisset Graben; Et-touhami, M. 2000) (Fig. 1).

The Atlas system is an intracontinental chain, resulting from the Cenozoic inversion of a Mesozoic rift system (Frizon de Lamotte et al., 2000; 2008; 2009 and references therein). South of the Rif, the NE-trending Middle Atlas is split into the tabular and folded Middle Atlas (Fig. 1). The tabular Middle Atlas consists of Triassic to Lower Jurassic weakly deformed sedimentary rocks extending over the Paleozoic terrains of the Western Meseta (Fedan, 1988; Charrière, 1990). The folded Middle Atlas shows large folds reactivating Jurassic salt ridges (Fedan, 1988). As in the Western Meseta, the Upper Miocene sediments of the foredeep basin occasionally lay directly on top of the Atlas Variscan basement, as observed north of the Tazzeka Massif (Fig. 5).

In the Eastern foreland, a moderately deformed Mesozoic sequence is characterized by Lower to Middle Jurassic carbonate platforms overlain by Upper Jurassic to Cretaceous turbiditic successions (Wildi, 1981; Hervouët, 1985; Zizi, 2002) (Fig. 4).

Within the foredeep, a "chaotic" mass of marls and clays, the "Prerif Nappe", is observed (Levy and Tilloy, 1952). It has been interpreted by Vidal (1977) as an olistostrome ("melange") or by Flinch (1994) and more recently by Flinch and Soto (2017) as an Upper Miocene accretionary prism. On top, the "Higher Nappes" correspond to better organized but strongly allochthonous units (Andrieux, 1971; Vidal, 1977; Leprêtre et al., 2018). In this category, we gather the Aknoul (Leblanc, 1979; Leblanc and Feinberg, 1982; Frizon de Lamotte, 1987b), Ouezzane (Suter, 1965) and Tsoul (Leblanc, 1979) Nappes (Fig. 1). The Aknoul Nappe, existing only in the Eastern Rif, exposes a more complete stratigraphic succession from the Lower Cretaceous to the Miocene (Top of Intrarif column in Fig. 4) whereas the Western-Central Rif equivalents Ouezzane and Tsoul Nappes, are mainly made of Cenozoic sediments with few Late Cretaceous shales at the bottom.

From a paleogeographic point of view, the Mesozoic foreland of the Rif belt corresponds to the former proximal domain of the North African Margin (Gimeno-Vives et al., 2019). As a consequence, the accommodation space and stratigraphic record during the Middle Jurassic to Cretaceous were significantly thinner than in the northernmost units.

3.2 The Mesorif Tectonic Windows (MTWs) and the Temsamane Units

The MTWs (Fig. 2, 3) were initially described in the Central Rif by Jean Marçais, who depicted their main features (Marçais *in* Durand-Delga et al., 1960-62): they correspond to anticline culminations developed after the emplacement of the Higher Nappes as indicated by the folding of their basal thrust-faults (Figs. 3 b,c and 6 a). They are supporting large thrust-sheets (i.e. the Senhadja and Higher Nappes) and late Miocene Wedge-Top basins (e.g. Dhar

Souk, Taounate, Boudinar Basins). Similar configuration is observed in the Eastern Rif where the "Temsamane Units" share the same structural position (Figs. 3 a and 6 b), although they are characterized by pervasive deformation and metamorphism.

3.2.1 The MTWs in the Central Rif

In line with the initial definition by Marçais (in Durand-Delga et al., 1960-62), we propose to enlarge the designation of the MTWs gathering previously misinterpreted units (details given in Table 1): the Internal Prerif (Bulundwe, 1986; Suter, 1981 a and b), the lower part of the Bou Haddoud Nappe (Leblanc, 1979), the Azrou Akchar Massif (Frizon de Lamotte, 1987b) and the Jebel Merzouk Massif (Favre, 1992) (Fig. 2). These units share a similar stratigraphic record and structural position, as emphasized by a widespread Oligo-Miocene sequence unconformably overlying the Mesozoic sediments. Apart from the Internal Prerif, the others were formerly interpreted as thrust-sheets and related either to Bou Haddoud or Senhadja Nappes (Leblanc, 1979; see Table 1).

In the MTWs (Fig. 7), the Paleozoic basement is not observed while the stratigraphic record goes from the Uppermost Triassic to the Middle Miocene, with a major unconformity – the Mesorif unconformity – between the Mesozoic-Paleogene and the Oligocene-Miocene successions (Fig. 4). The stratigraphic pile starts with Upper Triassic evaporites overlain by Lower to Middle Jurassic limestone and marly limestone, passing to Upper Jurassic to Upper Cretaceous turbidites. On top, few remnants of Eocene carbonates are described (Leblanc, 1979). The Mesozoic to Paleogene deposits are folded and faulted, as observed in the Tamda Window (Figs. 3, 7 c). This deformed Mesozoic to Paleogene succession is capped by an erosional surface defining the Mesorif Unconformity (Fig. 3, 7). The oldest formation, directly on top of the unconformity, consists of clastic Oligocene(?)-Lower Miocene sediments (Fig. 4). Stratigraphic dating of these sediments was performed across several localities of the Central and Eastern Rif by different authors (see Fig. 2 red dots). In the Tamda Window, these sediments range from Early to Middle Miocene (Vidal, 1977; Leblanc, 1979) (Fig. 6 a). In the Tifelouest Massif, they are slightly older, ranging from Oligocene to Early Miocene (Vidal, 1977; Favre, 1992). In this Massif, Eocene foraminifera were found in the clastic sequence directly on top of unconformity and interpreted as reworked within the Oligocene (?)-lower Miocene sediments (Favre, 1992).

3.2.2 The Temsamane Units in the Eastern Rif, correlations with the MTWs

The Temsamane Units widely crop out in the Eastern Rif (Fig. 2). They are bounded to the North-West by the Nekor Fault Zone (separating them from the Ketama Unit) and to the south by the Eastern Foreland (Fig. 2, 3 a). Upper Miocene-Pliocene basins such as the Boudinar

and Arbaa de Taourirt Basins developed along the Nekor Fault Zone (Fig. 2) and, as the Kert Basin, along the contact with the Eastern Foreland (Guillemin and Houzay, 1982; Fig. 1). The Temsamane Units correspond to a fold-and-thrust stack characterized by asymmetric south verging folds. Frizon de Lamotte (1985; 1987a) distinguished the South-Temsamane Unit and the North-Temsamane Units. Together, they represent external units cropping out below the Senhadja and Higher Nappes (Figs. 2, 3 and 6 b) and are therefore in a similar structural position than the MTWs described in the Central Rif. The South-Temsamane Units ["Nekor half-window" of Marçais and Suter in Durand-Delga et al. (1960-1962)] share with the MTWs the presence of an unconformable Oligocene-Miocene sequence (the Mesorif Unconformity) (Figs. 2, 4 and 6 b) resting over a folded and faulted Mesozoic sedimentary pile associated with a well-marked cleavage (Frizon de Lamotte, 1985). Separated from the South-Temsamane by a major tectonic structure (the intra-Temsamane Fault) (Fig. 3), the North-Temsamane Units display an intense ductile deformation characterized by a pervasive foliation bearing a ENE to NE stretching lineation (Frizon de Lamotte, 1985; 1987a; Negro et al., 2007; Booth-Rhea et al., 2012; Jabaloy-Sánchez et al., 2015) (Fig. 8).

At the top of the North-Temsamane Units (Ras Afraou and Tres Forcas), formerly interpreted as coming from the Internal Zones (Durand-Delga et al., 1960-62; Suter 1980 a & b), a MP-LT metamorphism is recorded [7–9 kbar and 330–430 °C (Negro et al., 2007)] contrasting with the almost non-metamorphic South-Temsamane Units. In Ras Afraou, the maximum metamorphic conditions are characterized by the assemblages of chlorite-phengite-quartz ± chloritoid ± kaolinite ± paragonite (Negro et al. 2007). The age of the Ras Afraou protolith was previously proposed as Paleozoic-Triassic (Frizon de Lamotte, 1985; Negro, 2005; Azdimousa et al., 2007). However, the recent paper by Azdimousa et al., (2019a), suggests a younger Cretaceous age, based on a population of detrital zircons in black shales dated at 243 ± 3 Ma. Nevertheless, the more classical Paleozoic-Triassic age cannot be completely disregarded at this stage. Based on field observations, age of the protolith post-dated the Paleozoic, given the Triassic to Middle Cretaceous ages of the North-Temsamane series (Frizon de Lamotte, 1985) and pre-dated the unconformable Upper Miocene (Tortonian) of the Boudinar and Kert basins (Guillemin and Houzay, 1982).

3.3 The Senhadja Nappes

The Senhadja Nappes extend from the easternmost External Rif (Khebaba Massif) up to the Central External Rif, where it was initially described (Suter and Marçais *in* Durand-Delga et al., 1960-62) (Fig. 2, 3). It is worth noting that like the Ras Afraou Unit (Temsamane), the Khebaba Massif was formerly interpreted as an element of the Internal Rif (Suter, 1980 a and b).

However, for different reasons explained below, a large majority of authors abandoned this hypothesis.

Suter and Marçais (in Durand-Delga et al., 1960-62) depicted the Senhadja as large thrust-sheets resting tectonically over the MTWs (Fig. 5 a). The geometry of the thrust-fault is especially well exposed around the Tamda Window (Figs. 7 d and 9 a), where the geometrical relationships between the Mesozoic and Cenozoic sequences of the MTWs (including the Mesorif unconformity) and the Senhadja Nappe are preserved. Within the Senhadja Nappes, two groups have been differentiated: the non-metamorphic Senhadja, and the metamorphic Senhadja. The first group corresponds to the Senhadja Nappe *sensu stricto*, well preserved in the Central External Rif (Figs. 2 and 9 b). The second group is made by discontinuous bodies dispersed over the Temsamane Units (Frizon de Lamotte, 1985) and the Eastern Foreland (Morel, 1980; Hervouët, 1985; Darraz and Leblanc, 1989) (Figs.2 and 9 a). The two groups show similar deformation history and stratigraphic succession (though with the notable absence of Oligo-Miocene cover) than the MTWs and the Temsamane Units, respectively.

3.3.1 Structures and origin of the Senhadja Nappes: A historical perspective

We precise below, from a historical perspective, the main controversies and the new elements provided for the multiple interpretations of the structure and origin of the Senhadja Nappes (Table 1). For Suter and Marçais (*in* Durand-Delga et al., 1960-62) and subsequently Leblanc (1979) and Wildi (1983), the Senhadja Nappe s.s. was a coherent thrust-sheet rooting within the Nekor Fault Zone (a huge "Triassic Mega-breccia", made of various blocks embedded in a gypsum matrix). In contrast, Vidal (1977) emphasized the "chaotic aspect" of the Senhadja and interpreted them as a mega-olistostrome ("melange") made of Mesozoic blocks of different nature and size, embedded in an upper Miocene sedimentary matrix (Table 1). For Vidal (1977), the origin of the allochthonous blocks was a domain located in-between the Intrarif and the Flysch Domain ("ultra-Ketama") as already proposed by Mattauer (in Durand-Delga et al., 1960-62) and Andrieux (1971) (Table 1). Both interpretations are reported in the 1:50000 cartography of the Central Rif, and kept on the posterior synthesis of Suter (1980 a and b). In the official geological maps published by the Geological Survey of Morocco (Suter, 1980 a and b), the major discrepancies existing along the sectors mapped by Vidal (1983) and the sectors mapped by Suter (1964) and Leblanc (1983) are still preserved. Posterior precise mapping by Papillon (1989) and Favre (1992), showed that the Vidal's (1977) Upper Miocene matrix frequently corresponds to dilacerated Upper Jurassic turbidites ("Ferrysch"). Recently, Gimeno-Vives et al. (2019; 2020) show that the "chaos" was inherited from the Late Triassic to Middle Jurassic rifting episodes, related to the opening of the Maghebian Tethys. They recognized typical rift-related raft in relation with salt tectonics and extensional detachment faults, which were

sampled during the Cenozoic mountain building processes. As a result, Gimeno-Vives et al. (2019; 2020) attributed the Senhadja Nappe *s.s.* to structurally distal elements of the Maghrebian Tethys passive margin. For these paleogeographic and structural reasons, a root zone located along the Nekor Fault Zone is favoured for the Senhadja Nappes (Wildi, 1983; Frizon de Lamotte, 1985; 1987b; Papillon, 1989; Favre, 1992).

Our current understanding of the structures and evolution of magma-poor rifted margins results from research conducted in the recent years and were therefore not known during the seventies. As a result, the structures observed in the Senhadja appeared very enigmatic for previous authors. This likely explains the success of the Vidal's (1977) misinterpretation, which has been adopted by other researchers (Frizon de Lamotte, 1981; Hervouët and De Luca, 1980). The misinterpretations of complex rift-related lithostratigraphic associations recorded in orogenic systems is not limited to the Rif belt. The same problem arose from other localities across the Alpine Chains as for the axial zone of the Western Alps (Beltrando et al., 2014) or the Middle East (Zagros, Taurus), with the so-called "coloured melanges" that were, at least partly, inherited from an early rifting episode (see discussion in Wrobel-Daveau et al., 2010).

3.3.2 Initial basement of the Senhadja Nappes, the specific question of Senhadja over the Temsamane Massif

The Senhadja nappe basement can be observed in several localities. In the non-metamorphic Senhadja of the Central Rif, this basement consists of mafic intrusive rocks (the Mesorif Gabbroic Complex), recently dated by U-Pb zircon dating yielding ages of 190-200 Ma (Michard et al., 2018; Gimeno Vives et al., 2019) (Fig. 4). The Mesorif Gabbroic Complex is interpreted as belonging to the Central Atlantic Magmatic Province (CAMP) and emplaced within the continental crust at the end of a Triassic rifting, then exhumed during a second Mid-Jurassic rifting episode (Gimeno-Vives et al. 2019; 2020).

In the metamorphic Senhadja, the basement consists of:

- a wide outcrop of Paleozoic rocks bearing MP-LT metamorphic assemblages (Negro et al., 2007) in the Khebaba Massif. The paragenesis is identical to the one observed at Ras Afraou, suggesting a common origin and geological history (Negro et al., 2007).

-smaller "blocks"(marble, gabbroic rocks, gneiss, kinzigite…) similar to the ones found in the Nekor "Mega-breccia". These blocks are included within the Triassic sole of the map or reworked in the Miocene sediments of the Foredeep; in both cases they rest below the Higher Nappes (Morel, 1980; Hervouët and De Luca, 1980; Frizon de Lamotte, 1982; Hervouët, 1985) (Fig. 4).

From a structural point of view, it is important to indicate that when the metamorphic Senhadja rest over the South-Temsamane Unit or the Eastern Foreland, they are tectonically sandwiched between the autochthonous Miocene sediments and the Higher Nappes (Aknoul Nappe) as expressed in the figure 6 b. By contrast, when it rests over the North-Temsamane Units, a basal major shear zone is documented, without evidence of Miocene sediments below.

3.4 The Tifelouest-Tafraout Unit

North of the Nekor Fault Zone, and separating the MTWs from the Ketama Unit, the Tifelouest-Tafraout Unit corresponds to the transition between the Mesorif and the Intrarif (Fig. 2). The contact between the Mesorif and the Tifelouest-Tafraout Unit is interpreted as a thrust-fault although covered by the Upper Miocene Dhar Souk Basin (Fig. 3 c). Despite its structural position, directly adjacent to the Ketama Unit, the Tifelouest-Tafraout Unit displays a similar Mesozoic sedimentary sequence than the Senhadja Nappe and the MTWs (Fig. 4). It is characterized by Upper Triassic evaporites at the base, with Lower Jurassic carbonates on top, overlaid by Middle Jurassic marls and Upper Jurassic to Lower Cretaceous turbidites (Favre, 1992). Importantly, Favre (1992) documented a sequence of compressional deformation beginning during the Late Eocene and going on during the deposition of the Oligocene. This early antiformal stacking (described as duplexing) was reactivated and accentuated after the deposition of the Lower to Middle (?) Miocene and the emplacement of the Higher Nappes.

3.5 The Ketama Unit

The Ketama Unit is a far travelled unit, belonging to the Intrarif. Together with the Higher Nappes, it corresponds to the structurally higher elements of the External Rif nappe stack, overlaying all the previously mentioned units. From a litho-stratigraphic point of view, the Ketama Unit consists of a ca. 2800 m thick Mesozoic sequence (Andrieux, 1971; Fig. 4). Its substratum displays a different nature from south to north, passing from a hyperextended continental crust in the south, to an exhumed mantle in the north (Michard et al., 1992; Gimeno-Vives et al., 2019).

In the south, it consists of a Lower Jurassic carbonate platform overlying a highly tectonized Upper Triassic evaporitic level (see the Arbaa de Taouirt and Sof Aouzzai outcrops in Gimeno-Vives et al., 2019) and covered by an Upper Jurassic turbiditic sequence. In the north, in the Beni Malek Massif, the substratum corresponds to serpentinized peridotites interpreted as a former exhumed mantle domain of the North African margin formed during the Tethys rifting in the Continent-Ocean transition (Michard et al., 1992; Gimeno-Vives et al., 2019; 2020). Since the Upper Jurassic, the southern and northern parts of the Ketama Unit show the same stratigraphic succession (Mattauer, 1958; Durand Delga et al., 1960-62; Andrieux, 1971; Frizon de Lamotte,

1985). The Upper Jurassic ("Ferrysch" Fm) (Wildi, 1981) and the Aptian-Albian sequences are characterized by the deposition of turbidites, with deposition of marls in-between. The top of the Ketama Unit shows carbonates and marls deposited during the Cenomanian and Turonian.

The Ketama Unit has been folded and foliated during the Cenozoic, recording a variable metamorphism, ranging from very low to low-grade greenschist-facies conditions along the Nekor Fault Zone (Andrieux, 1971; Frizon de Lamotte and Leikine, 1985; Leikine et al., 1991; Azdimousa et al., 1998; Vázquez et al., 2013). Two deformation phases are described (Andrieux, 1971), a first phase corresponding to a slaty cleavage (S1) parallel to the layering associated to large scale recumbent folds (Fig. 10), and a second phase corresponding to the subsequent folding of the (S1) by asymmetric folds with an axial plane foliation (S2) defining a crenulation cleavage.

In the southern part of Ketama, outcrops exposing a "Triassic mixture" are documented (the so-called "accidents à Trias"), consisting of faults filled by Triassic evaporites (Andrieux, 1971; Frizon de Lamotte, 1985). Partly, due to dissolution process, only few evidence of salt or gypsum is reported, and the mixture is made mainly of exotics elements [basement blocks, Triassic (?) red beds, limestone]. It was interpreted as injections under high fluid pressure coeval with the individualization of the nappes (Frizon de Lamotte, 1985; Frizon de Lamotte and Leikine, 1985). We rather consider that they correspond to former salt walls and salt canopies emplaced during the Cretaceous in the distal part of the margin, as observed along the Central Atlantic margin (Hafidet al., 2008; Tari et al., 2017; Deptuck and Kendell, 2017), in the Subbetic (Soto Flinch and Tari, 2017; Escosa et al., 2018) and in the Algerian and Tunisian Tell (Vila, 1980; Vila et al., 1996; 1998). Scarcity of evaporites may also suggest welding of the conduits after the transit of the salt and associated elements. We note that the salt canopies may represent ideal structures to decouple the Higher Nappes from Ketama during the Cenozoic.

3.6 The Higher Nappes

Structurally on top of the tectonic pile, the Higher Nappes are emplaced over the Senhadja Nappes, the MTWs and the foreland (Fig. 2, 3). There is a consensus to consider that they represent far-travelled gravitational nappes detached from the Ketama Unit (Suter, 1965; Andrieux, 1971; Vidal, 1977; Leblanc, 1979; Wildi, 1983; Frizon de Lamotte, 1987; Frizon de Lamotte et al., 1991; Booth-Rhea et al., 2012). Among the Higher Nappes, we can differentiate from west to east: the Ouezzane, Tsoul and Aknoul Nappes (Fig. 1). Ouezzane and Tsoul Nappes, that do not crop out in the study area, are mainly made of Cenozoic rocks (see above). Aknoul Nappe covers large areas in the Central and Eastern Rif and preserves the Upper Cretaceous to Miocene deposits of the Intrarif.

At the base of the Aknoul Nappe Aptian-Albian turbidites are exposed, as in the Ketama Unit. From the Upper Cretaceous up to the Eocene, the Higher Nappes consist of marls and pelites, culminating with the Numidian flysch at the top (Fig. 4 and 11). Contrasting with the MTWs, no unconformity can be observed between the Paleogene and the Oligocene-Miocene series (Leblanc and Feinberg, 1982). The stratigraphic succession of the Ketama and Aknoul Units are complementary, demonstrating that they pertain to the same basin (Frizon de Lamotte, 1987) (Fig. 4). In general, the Higher Nappes are poorly deformed, without any metamorphism, except for the very base of the Aknoul Nappe (Frizon de Lamotte and Leikine, 1985). The Aknoul Nappe is also characterized by large exposures of Upper Triassic evaporites. They are related to former salt canopies preserved in the Upper Cretaceous marls (Fig. 12). Some of them have been used to decouple the Aknoul Nappe from its Ketama initial substratum, lying along the Aknoul basal thrust fault (Fig. 2). Others were interpreted as "frozen" before the Aknoul translation, allowing the preservation of former salt canopies in the field (Fig. 12).

3.7 Wedge-top Basins

Upper Miocene to Pliocene basins developed on top of the orogenic wedge i.e. the Higher nappes and MTWs. They are distributed close or along the Nekor Fault Zone (Figs. 1 and 13) and were formerly interpreted as "post-nappes" basins (Morel, 1988 and references therein). In fact, these basins were developed during the late activity of the orogenic prism and formed what is generally called "wedge-top basins" (see a review in Leprêtre et al., 2018).

From a paleogeographic point of view, they constitute the north-Rif Corridor, a seaway present during the Tortonian (the Messinian is not recognized except in the eastern basins, like the Boudinar and Kert basins) (Wernli, 1987). The north-Rif Corridor allowed water exchange between the Atlantic and Mediterranean Domains (see a review in Capella et al., 2017). The sedimentary succession of these basins is characterized by an alternation of clastic deposits, with conglomerates at the base, continuing with more marly deposits towards the top. The whole succession can reach 2000 m (i.e. the Taounate basin) (Samaka et al., 1997).

The sedimentation in these basins was controlled by extensional faults bordering the basins to the south. These are giving birth to spectacular half grabens, well illustrated by the seismic lines (Samaka et al., 1997; Leprêtre et al., 2018) (Fig. 13). They are indicative of an important collapse of the orogenic system during the Tortonian. However, in the Central Rif, the basins display a syncline shape, with steep flanks due to a post-Tortonian (perhaps starting as early as the Late Tortonian) NW-SE compression (Morel, 1988; Samaka et al., 1997; Capella, 2017).

4. Review of existing geochronology and thermochronology studies in the External Rif and new data

To complement the study of the structural units of the External Rif, we performed thermochronological analyses on apatite on two samples from the Mesorif gabbroic complex of the Senhadja Nappes: Bou Adel and the Jebel Baïo (Figs. 2, 14). Before presenting these results, we review the existing thermochronological data of the literature. We firstly present a summary of the results from the different dating methods (apatite/zircon thermochronology, K/Ar and $^{40}Ar/^{39}Ar$ datings) performed on the Intrarif (Ketama Unit) (Azdimousa et al., 1998; Vázquez et al., 2013), the Flysch domain (Azdimousa et al., 2003; Romagny, 2014) and the Temsamane Massif (Monié et al., 1984; Negro et al., 2008; Jabaloy-Sánchez et al., 2015). Locations and petrography of the various samples are shown on figure 14 and detailed results can be found in the supplementary files (Tables S1-S4; Fig. S1-S7; Text S1, S2).

4.1-Critical review of existing data

- *Ketama/Flysch domains*

Two general observations can be done for the Central-Eastern External Rif/Flysch domain (excepting the Temsamane Massif that will be discussed after):

(1) Important differences exist between apatite, zircon and micas/amphibole dating results. Apatite thermochronology shows systematically values younger than 20 Ma, whereas zircon and micas/amphibole dating values span the Paleozoic-Late Cretaceous interval [*Apatite and zircon fission track dating*: Azdimousa et al., 1998; 2003; *micas/amphibole dating*: Azdimousa et al., 1998 (K-Ar); Jabaloy-Sánchez et al., 2015 ($^{40}Ar/^{39}Ar$)];

(2) Many of these data need to be taken cautiously. Indeed, they do not provide all the methodological requirements to be considered valid, or suffer from a lack of precisions to be adequately interpreted (see "Basic principles" contributions in Malusà and Fitzgerald, 2019 for the interpretation of apatite and zircon fission track data – AFT and ZFT data, respectively). We detail in the following, the numerous issues about their use.

The apatite dataset, which is spatially scattered (Fig. 14 d), is sampling detrital rocks, from Callovian-Oxfordian to Aptian-Albian rocks (Azdimousa et al., 1998, 2003; Romagny, 2014), with a very low amount of dated grains for each sample (see above references; for this methodological requirement, see Vermeesch et al., 2007). This is usually problematic since different sources, with thus different age signatures, can contribute to the values range. Fortunately, the apatite fission-track results are unequivocally showing well-grouped ages significantly younger (< 20 Ma) than their own stratigraphic ages (by more than 80 Ma). This means they have been fully reset and might be roughly handled as if they were deriving from a

single exhumed domain. However, the apatite dataset also suffers from the absence of fission-track lengths measurements, which prevents a refine interpretation of the AFT data in terms of thermal story.

In the Flysch Domain, one AFT age of 18 ± 1 Ma and two apatite (U-Th-Sm)/He (AHe) data with mean ages of 9± 2 Ma and 8± 4 Ma are published (Azdimousa et al., 2003; Romagny, 2014). In the Ketama Domain, four AFT ages ranging from 14± 3 to 20 ± 2 Ma exist, from Aptian-Albian and Callovian-Oxfordian series (Azdimousa et al., 2003). These results are consistent with stratigraphic data showing that in both, Flysch and Intrarif Domains, the youngest sediments preserved are Aquitanian (23-20.5 Ma). This suggests that the exhumation in these domains rapidly followed the most recent sedimentary deposition (Fig. 4). We consider that the exhumation also marks the individualization and the onset of gliding of the Higher Nappes forming initially the top of the Intrarif Domain.

The zircon fission-track (ZFT) dataset of Azdimousa et al. (1998; 2003) comes from the same rock samples than the apatite dataset, which were – when possible – double-dated. Contrary to the apatite, these dating results are not grouped and span a huge time interval from Paleozoic to Cretaceous. The youngest zircon sub-population is dated from 75 to 100 Ma (9 ages of 44 zircons in total). For this "young" sub-population, ZFT datings are always showing older ages than the stratigraphic ages of the samples. It means that reset had been very partial, for this thermochronometer assuming a closure temperature ranging from 140 to 220°C (e.g. Guenthner et al., 2013). Some authors suggested to tie the 75-100 Ma ages interval to the K/Ar dating results (78±1.2 and 81.6 Ma±4.0) through a similar thermal event occurring during this time range (Azdimousa et al., 1998; 2003; Vázquez et al., 2013).

The existing K/Ar dating results from Azdimousa et al. (1998) are in the 78-82 Ma and the 127-132 Ma ranges. These ages are questionable for two reasons. First, they dated very low-grade rocks with fractions < 2 μm which can give doubtful results [see comment by Michard et al. (2015) on Vázquez et al. (2013)]. Second, the authors did not provide microstructural and petrographic constraints to their dating. Indeed, the absence of precise petrographic constraints allows the possibility of age mixtures for these samples since the area is known for at least two deformation events (Andrieux, 1971; Frizon de Lamotte, 1985). The unequivocal meaning – and thus the interpretation – of these dating results has been the fuel for debates that show the difficulties to use them (Vázquez et al., 2013; Michard et al., 2015).

- *Temsamane Massif*

The existing geochronological data of the metamorphic North-Temsamane Units include $^{40}Ar/^{39}Ar$ dating (Monié et al., 1984; Negro et al., 2008; Jabaloy-Sánchez et al., 2015) and U-Pb

Zircon dating (Azdimousa et al., 2019a). The majority of the $^{40}Ar/^{39}Ar$ dating yields late Oligocene-Miocene ages interval. In detail, three groups were initially defined by Negro et al. (2008).

A first group, spanning the 23-33 Ma interval, related to the metamorphic peak recorded by the MP-LT metamorphic suite. It is similar to ages already found by Monié et al. (1984) between 25 and 28 Ma and lately confirmed by Jabaloy-Sánchez et al. (2015) with 30-33 Ma ages for deformed Paleozoic rocks equivalent to Ras Afraou Unit (Negro et al., 2008). This first age range corresponds to a minimum age for the MP-LT metamorphic peak that likely occurred by the end of Eocene or early Oligocene, as already advocated by Negro et al. (2008).

A second group, bracketed between 15 and 12.5 Ma by Negro et al. (2008), was related to the development of the main foliation. This range was extended down to 21 Ma by Jabaloy et al. (2015) with dating on amphibole from the "Taliouine Unit", within the North Temsamane stack. This age range is related to a second stage of ductile deformation recording a protracted exhumation phase, dominated by top-to-the-WSW tectonic transport (see above).

At last, a third group, displaying younger ages up to 7-8 Ma (Monié et al., 1984; Jabaloy-Sánchez et al., 2015), has been related to the late stages of the metamorphic rocks exhumation (Booth-Rhea et al., 2012; Jabaloy-Sánchez et al., 2015; Azdimousa et al., 2019b). This last phase, corresponds chronologically to the emplacement of the Higher Nappes and, finally, to the fault-related development of the wedge-top Tortonian basins (i.e. Arbaa de Taourirt, Boudinar and Kert basins)(Guillemin and Houzay, 1982).

4.2-New AFT and AHe data from the Senhadja Nappes

- *Methods*

With the development of the apatite low-temperature thermochronology since the 1980's (*apatite fission track dating*: Green, 1981; Gleadow et al., 1986; *apatite helium dating*: *e.g.* Wolf et al., 1996; Shuster et al., 2006; Flowers et al., 2009; Gautheron et al., 2009), a new tool has become available to reconstruct the thermal history for the 40-90°C (AHe: Farley, 2000; Shuster et al., 2006) and 60-110°C (AFT: *e.g.* Gleadow andDuddy, 1981) thermal domains of the upper crust *i.e.* the 3-4 first kilometers of the crust. These two apatite geochronometers are indeed sensitive to "cold" closure temperatures (Dodson, 1973). Inverse and forward thermal modeling allow the user to test and find thermal paths that are able to reproduce the apatite dataset within acceptable error bars (Ketcham, 2005; Gallagher, 2012 and references therein).

Two gabbros belonging to the Senhadja Nappes were sampled for this work: the Bou Adel (RE27) and the Jebel Baïo (RE47) (Location and Petrological description are given in table

2 and S2 respectively). Samples were prepared following classical procedures (*e.g.* Leprêtre et al., 2015). For AFT dating, a minimum of 20 grains were selected. Fission-track counts were done with the external detector method (Galbraith and Laslett, 1993; with zeta (J.B.) of 348 ± 3) and determination of central age was done following Hurford and Green (1983). Irradiation was carried out in the reactor of Garshing in Germany. No fission-track lengths could be measured for both samples. For AHe dating, a minimum of 6 and 7 grains were dated in Tübingen (C. Glotzbach). Then, thermal modeling was done using QTQt (Gallagher, 2012).

- *Results (Table 2)*

Only Bou Adel (RE27) sample was dated through AFT because Jebel Baïo (RE47) apatites were of poor quality for this method. On the contrary, both samples were dated with AHe method. RE27 sample gave an AFT age of 17 ± 2 Ma, whereas AHe dating gave single-grain (corrected) ages ranging from 6 ± 0.5 Ma to 25 ± 2 Ma for RE27, and from 5 ± 0.5 Ma to 29 ± 2 Ma for RE47. For both samples, AHe dating results show two similar pools of ages. A first one shows a 5 to 12 Ma single-grain ages interval (n=12) whereas a second one shows significantly older ages, from 17 to 29 Ma (n = 3). No parameters are able to explain this difference in terms of radioactive isotopes proportions (see Table 2): the Th/U ratio is similar between the grains; the eU are not different enough either. Also, the size of grains and Ft correction (Farley et al., 1996; Ketcham et al., 2011; Gautheron and Tassan-Got, 2010) parameters cannot account for this. We suggest for this minority of older grains a possible implantation effect could provoke this «ageing», by an artificially increased amount of ^{4}He provided by surroundings crystals in the rock (Gautheron et al., 2012). As result, these 3 grains will not take into account for the thermal modeling.

- *Thermal modeling*

We only provide here the final results showing the best fit between the predicted versus observed data, which respects the geological constraints obtained from field observations. As to set aside comments regarding the use of stratigraphic and tectonic field observations in our thermal modelings, we would like to precise for non-familiar users of low-temperature thermochronology that many solutions can be found with a single dataset, even when AFT (age & lengths) and AHe are both available. As an example, Leprêtre et al. (2014, 2015) showed that in some cases, not using the stratigraphic constraints leads to propose statistically consistent thermal models that are geologically meaningless. We thus made the decision to incorporate the stratigraphic and tectonic information in our modeling process. The different stages of the modeling are presented and described in details in the supplementary data (Text S1; Fig. S4-S7).

The thermal modeling of Bou Adel-RE27 (Fig. 14) is the most complete, given the double AFT-AHe dataset. The best model incorporates the following geological constraints: (1) the gabbro massif, dated at 190-200 Ma (Gimeno-Vives et al., 2019), was emplaced within the continental basement, which was subsequently buried under thick syn- to post-rift sequences. Therefore, it has been kept at a minimum depth of few kilometers during its whole Mesozoic history, at least up to the Late Cretaceous and the first stages of convergence (Gimeno-Vives et al., 2019); (2) Given the similar origin for the Senhadja Nappe s.s. and the MTWs, the existence of the Mesorif Unconformity sealing up a pre-Miocene deformation within the MTWs, it implies that the Bou Adel gabbro was at or close to the surface before the late Oligocene(?)-early Miocene period; (3) the sample is currently at the surface. The thermal path of the Bou Adel gabbro (the Senhadja Nappes) shows a long and hot Mesozoic history at temperatures higher than 110°C, preventing remnants of old AFT and AHe dating results. The gabbro underwent cooling then up to the Eocene-Oligocene and temperatures close to surface (30-40 ± 10°C) before a re-heating event that was quick and strong, reaching up to 100°C maximum temperatures. Then, constrained by the AHe datings, thermal paths are all showing the same trajectory, with a last cooling from 11-13 Ma up to the present-day and surface conditions (20 ± 10°C).

The thermal modeling of the Jebel Baïo-RE47 (Fig. 14) was carried with only AHe datings. It furthermore belongs to a more complex structural context since it is a kilometric gabbroic Massif embedded into the Nekor Fault breccia (Fig 2). As for the last cooling part of the RE27 sample, the Jebel Baïo Massif cooled during the Late Miocene-Quaternary stage from temperatures higher than 100°C up to surface conditions.

5. Discussion

After revising the structure and chronology of deformations of the External Rif, we propose and discuss an up-dated geodynamic evolutionary model. We will focus successively on the events occurring before and after the Mesorif Unconformity. Concurrently, we will propose a new set of paleogeographic maps and schematic cross-sections, illustrating these geodynamic events.

5.1 The pre-Mesorif Unconformity deformation: the role of the under-thrusting of the North African margin below the Maghrebian Tethys

The existence of an important compressional tectonic event during the Middle-Late Eocene is a common feature of the Tethys Realm. In the West Mediterranean, it is identified in the Iberian Chain (Roca and Guimera, 1992), the Pyrenees (Muñoz, 1992; Vergés et al., 1995; Vergés et al., 2002) and the Alps (Schmid et al., 1996; Beltrando et al., 2010). It is understood as

the result of the collision between Eurasia-Iberia or Eurasia-Apulia intervening microplates (e.g. Handy et al., 2010; Van Hinsbergen et al., 2019).

In North Africa, this period corresponds to the major compressional event of the Atlas System (Laffitte, 1939; Frizon de Lamotte et al., 2000; 2009; 2011; Khomsi et al., 2009; 2016). Along the North African margin (i.e. in the Tell-Rif), pre-Miocene deformations, sealed by an unconformity equivalent to the "Mesorif unconformity", were also recognized (e.g. Delteil, 1974; Fenet, 1975). However, the importance of these deformations has often been minimized in the geodynamic reconstructions. Contrasting with the large imprint of this tectonic event at the scale of the West-Mediterranean, the still open Maghrebian Tethys (i.e. the Intrarif and Flyschs domains) remained weakly deformed at that time.

Studies by Negro et al. (2007; 2008) in the Eastern Rif, show that in the Temsamane Massif, the Ras Afraou and Khebaba Units underwent a "subduction-related" medium-pressure low-temperature (MP-LT) metamorphism (7-9 kbar, 330-430°) with peak conditions at possibly 30 Ma, or earlier. Even though the interpretation assigning an internal origin for the Ras Afraou and Khebaba Units (Suter and Marçais in Durand-Delga et al., 1960-62) was generally abandoned after Frizon de Lamotte (1985), Negro et al. (2007) did not decide between an internal (i.e. between Alboran and the Maghrebian Tethys) or external (i.e. between the North African margin and the Maghrebian Tethys) position for this under-thrusting zone. However, as indicated by Leprêtre et al. (2018), in line with Faure-Muret and Choubert (1971), Frizon de Lamotte (1985; 1987), Michard et al. (2007), Chalouan et al. (2008) and Booth-Rea, et al. (2012), an external position is the only configuration consistent with the large-scale geometry. In particular, as already presented and discussed above, the location of the Temsamane Massif corresponds to a "Mesorif-equivalent" structural position, below both, the Senhadja and Higher Nappes (Fig. 6 b). This is also supported by the continuous increase of the metamorphic conditions from the Eastern foreland to the chloritoid-bearing rocks of the Ras Afraou Unit in Temsamane (Frizon de Lamotte and Leikine, 1985; Booth Rea, et al., 2012) (Figs. 2, 3 a and c). Therefore, the structural position and the MP-LT metamorphic conditions in the Temsamane Units, involve an under-thrusting of the North African margin beneath the deep basin of the Maghrebian Tethys (the Intrarif Zone-Ketama and the Flyschs Domain) (Figs. 15 a and 16). Alternative interpretations (Booth-Rea et al., 2012.) considered the Temsamane Massif as a Metamorphic Core Complex. However, no rocks or structures from hanging wall to footwall can be connected to the supposed detachment fault and no breakaway structure has been identified. Therefore, we consider that the frequent younger-over-older tectonic contacts are better explained by out-of-sequence thrusting of the Higher Nappes over the North Temsamane Massif (Fig. 6 b).

Laterally, in the Central Rif, the MTWs also preserve the evidence of pre-Miocene deformation, sealed by the "Mesorif Unconformity" (Fig. 7) while no metamorphism is documented. Therefore, given their structural position in the lower plate of the system, we intend that the Senhadja Nappe s.s and Tafraout-Tifelouest Units acted as a "buffer" (a kind of accretionary prism) between the MTWs and the under-thrusted units (Figs. 15 a and 16).

The under-thrusting of a rifted margin beneath a deep basin is unusual but not odd. This configuration is well-documented in Oman, between 95 and 75 Ma, when the obducted Semail ophiolite emplaced over the Arabian Margin in relation with an incipient subduction (i.e. Agard et al., 2010). It was similar in New Caledonia, between 45 and 30 Ma, when the continental Norfolk ridge was subducting below the South-Loyalty oceanic basin (Cluzel et al., 2001; Lagabrielle et al., 2013; Patriat et al., 2018). In these two examples, a true HP-LT metamorphic signature is observed in tectonic windows, the Saih Hatat and Mont Panié domes respectively, piercing a wide ophiolitic nappe.

In the Eastern external Rif, as in New Caledonia and Oman, even if the metamorphic record is less severe, continental under-thrusting is well documented. Considering the similarities between the Temsamane and the Algerian EMMs (Fenet, 1975; Guardia, 1975), the under-thrusting zone can be extend eastward up to Greater Kabylie (Figs. 1 and 15 a'). It absorbed a part of the convergence between Africa and Eurasia prior to the Oligocene, i.e. up to the closure of the West-Ligurian Tethys, the western branch of the Alpine Tethys located between Iberia and AlKaPeCa (Leprêtre et al., 2018)(Fig. 15 a'). Therefore, we emphasize the correlation between the Middle-Late Eocene far-field deformation in Western Africa and Western Europe, and the peak conditions of the MP-LT metamorphism along the North African margin, under-thrusted below the Maghrebian Tethys. All these events are themselves correlated with the onset of the oceanic subduction of the Maghrebian Tethys below AlKaPeCa (Figs. 15 a and 16). Laterally, the deformation was recorded within the MTWs in the Mesozoic-Paleogene cover. It was likely associated with tectonic stacking, leading to local culminations (Fig. 3 c, 6 a and 7), responsible for the erosion, which gave birth to the Mesorif Unconformity, below the Oligocene(?)-Miocene deposits (Fig.16).

5.2 The post-Mesorif Unconformity deformation: (1) Onset of the Maghrebian Tethys subduction, Exhumation of the EMMS and Senhadja individualization

At large scale, the Eocene-Oligocene transition corresponds to a major geodynamic change in the West-Mediterranean (Fig. 15 b). From this period onward, the accommodation of the convergence was transferred to the northward subduction of the Maghrebian Tethys below AlKaPeCa (Fig. 15 b'). This new regime of subduction progressively closed the Maghrebian

Tethys, coeval to the opening of the West Mediterranean back-arc basins (e.g. Vergés and Sàbat, 1999; Jolivet et al., 2000; Frizon de Lamotte et al., 2000; Jolivet et al., 2008).

Along the whole North African margin and, in particular, in the Temsamane Units, the Eocene-Oligocene boundary marks the metamorphic climax followed by the exhumation onset. We propose that the individualization of the metamorphic Senhadja Nappe results directly from this geodynamic process (Fig. 16). As indicated above, the metamorphic Senhadja Nappe corresponds to Paleozoic or Mesozoic material buried during the under-thrusting of the North African margin, then exhumed and, finally, dragged at the bottom of the Higher Nappes (Fig. 6 b). During the exhumation, shear zones developed at the base and below the metamorphic Senhadja. Geometrically, they correspond to ramps, emplacing older rocks (Paleozoic micaschists, Jurassic marble) over already deformed younger rocks (Cretaceous foliated marls) (Fig. 6 b). During the Middle Miocene, and before the emplacement of the Higher Nappes on top of the Temsamane and the Eastern Foreland (see below), the metamorphic Senhadja was exposed at the surface and eroded (Fig. 15 b). This is proven by the presence of reworked metamorphic material in the autochthonous Miocene covering both the South-Temsamane Units and the Eastern Foreland (Morel, 1980; Hervouët and De Luca, 1980; Hervouët, 1985; Frizon de Lamotte, 1985). The structural disposition of the metamorphic Senhadja recalls the "nappes à affinités rifaines" (Rif-like nappes) of Guardia (1975) found at the Algeria-Morocco border, in the Tell. There, these units display clear pre-Miocene deformation, acquired before the emplacement of these nappes on top of Miocene sediments.

More to the west, the non-metamorphic Senhadja Nappe is a structural element distinctive of the Rif, having no equivalent in the Algerian Tell. As discussed before, there is a large consensus to consider the root zone of the Senhadja Nappes as a domain initially located west of the Temsamane, between the MTWs and the Tafraout-Tifelouest Units (Fig. 15 a). Actually, the restoration of the Ketama Unit to its initial position freed up a space at the north of the Rif basin, where it joins the Maghrebian Tethys (Fig. 15 a). Such an interpretation is consistent with the paleogeographic affinities of the Senhadja, sampling the North African distal margin (Favre et al., 1991; Favre, 1992; Gimeno-Vives et al., 2019).

The propagation of the North-Maghrebian subduction continued westward (Fig. 15 b') and crossed the Nekor Fault Zone, entering within the Rif basin. At this moment, it split into several SW-verging thrust-faults delimiting distinct tectonic Units: the non-metamorphic Senhadja and Tifelouest-Tafraout Units (Fig. 15 b). The propagation of the deformation south of the Nekor Fault Zone in the Western and Central Rif is strongly constrained by the initial configuration of the North African margin with "en echelon" NE-SW trending oblique basins (the Rif basin).

Compared to the MTWs of the Central Rif, the non-metamorphic Senhadja Nappe presents two typical features: it is poorly deformed and does not preserve Cenozoic records (Fig. 4). The weak deformation can be explained by the thick Upper Triassic sole present in the Rif basin, favoring the decoupling between the Mesozoic cover and the crustal basement. In line with the thermal history of the Bou Adel gabbro (Fig. 14) that shows slow cooling since the Early Cenozoic (~1-2°C/Ma ≈ 30-50m/Ma assuming a geothermal gradient of 30°C/km) the displacement of a nappe without significant internal deformation could explain that it has not be eroded as fast as it would be with important thrust-faults or folding. The coeval crustal stacking at depth (Fig. 16) triggered an uplift and the subsequent erosion of the Senhadja Cenozoic cover. The decoupling between the cover and the basement [except for the so-called Mesorif gabbroic complex, attached to the cover (Gimeno Vives et al., 2019)] allowed the southward lateral gliding of the cover (Figs. 15 b and 16). Thus, the sedimentary cover of the northernmost part of the Rif basin was thrusted over the Early Miocene sediments of the MTWs (Leblanc, 1979), founding the Senhadja Nappe. In contrast, the stacking of the Senhadja initial basement, resting west of the Nekor Fault Zone, contributed to the crustal thickening below the Western Rif (Mancilla et al., 2012; 2015; Petit et al., 2015). By reference to the deformation sealed by the Mesorif Unconformity, the thrusting of the non-metamorphic Senhadja is out of sequence. Nevertheless, it occurred early during the sedimentation of the Miocene sequence as shown by syn-sedimentary tectonic stacking observed in the Tifelouest-Tafraout Unit (Andrieux, 1971; Favre, 1992).

From paleogeographic and tectonic arguments, we assume that the Senhadja s.s. was close to the surface from 35 Ma (Mesorif Unconformity) to 20-18 Ma (emplacement of the Nappe). Accordingly, the thermal modeling of the thermochronological data indicates that, after 25-20 Ma, the Senhadja was buried to a depth of about 3-4 km and subsequently exhumed since 10 Ma (see Fig. 14; considering a gradient of 30°C.km^{-1}). This post-20 Ma evolution strongly differs from the Temsamane, which from 20 Ma to present underwent a continuous exhumation (Figs. 15 b and 16).

5.3 The post-Mesorif Unconformity deformation: (2) Alboran westward translation, foreland flexuration, far-travelled gravity-driven nappes, wedge-top basins and late contraction

From the published low-temperature thermochronological data (Azdimousa et al., 1998, 2003), the compressional deformation reached the Intrarif (Ketama Unit) between 20-15 Ma (Fig. 15 b); that is to say just after the deposition of the Numidian Flysch (Aquitanian; 23-20 Ma) and likely before the docking of the Kabylie Massifs along the Algerian paleo-margin, which is older than 17 Ma (Chazot et al. 2017) (Fig. 15 c). The contractional deformation in the Ketama

Unit corresponds to the development of an accretionary prism in front of the westward moving Alboran Domain. It is expressed by a stack of spectacular recumbent folds (Fig. 10), involving only the sedimentary cover. This tectonic style has a major implication: The initial basement of Ketama Unit was decoupled from its cover (except small slices like the Beni-Malek serpentinized peridotites) and subducted below the Alboran Domain. Therefore, the current basement of the Ketama Unit is likely the leading edge of the North-African margin, and not its initial "oceanic" substratum preserved in the Beni Malek Massif (Michard et al., 2002; 2007; Gimeno-Vives et al., 2019);

During the westward movement, the tectonic stack (duplex) formed by the Ketama Mesozoic cover reached the EMMs, while its exhumation was still in progress. The result is the development of a relief, allowing the decoupling of the roof of the Ketama duplex along former Upper Triassic salt canopies, individualizing the Higher Nappes (Fig. 15 c and 16). This individualization is likely recorded by the thermochronology with the 20-15 Ma AFT ages in the Ketama unit below, evidencing an important cooling, corresponding to the unit unroofing. They were pushed south-westward by the moving Flyschs Units and further started to glide over the already emplaced Senhadja Nappe. After the Higher Nappes emplacement, the non-metamorphic Senhadja recorded their transient passage on top of the prism, since it coincides between *c.a.* 20 and 10 Ma to a 3-4 km of burial recorded in Bou Adel and Jebel Baïo (Fig. 14). The out-of-sequence nature of this tectonic contact over the Senhadja, explains why this thrust-fault put young material over older already eroded rocks. The final exhumation of the Rif foredeep is associated with Tortonian (8.5 to 7.25 Ma) extensional formation of the wedge-top basins followed by a general NW-SE contraction still active currently (Fig. 13).

6. Conclusion

A review of existing literature, combined with new structural and thermo-chronological data, allows us to revisit the structure of the Central and Eastern External Rif and unify the local interpretations proposed since the pioneer synthesis of Durand-Delga (1960-62). The main units identified in the External Rif can be described as follows from bottom to top: (1) A frontal foredeep (Prerif) resting over a flexured foreland; (2)The Mesorif Tectonic Windows (MTWs), including the North-Temsamane (bearing pre-Oligocene MT-LT metamorphic assemblages); (3) The Senhadja Nappe resting over the MTWs and the foreland; (4) The Ketama Unit (Intrarif) and (5) The Higher Nappes representing far travelled thrust-sheets detached from the Ketama Unit resting over the MTWs, the Senhadja Nappe and the foreland.

We addressed several long-standing debates regarding the evolution and origin of key units of the External Rif. The metamorphic North-Temsamane Massif is an integral part of the

External Rif. Its exhumation combined the coeval development of compressional and extensional structures. Invocation of "Metamorphic Core Complex" is not useful. Regarding the Senhadja Nappe, our results confirm that this nappe originated from the foot of the North-West African paleomargin. Its apparent chaotic aspect and puzzling structure were both inherited from the Mesozoic rifting. Therefore, all previous explanations, relying on Cenozoic "disintegration" (olistostrome, melange), must be abandoned, accordingly. By contrast, the weak deformation observed in the Higher Nappes results from their origin in a preserved post-rift succession and from their mode of individualization and emplacement: detachment and gliding from former salt canopies.

We emphasize the role of the pre-Miocene compressional deformation recorded in the External Rif. Although this event was already recognized, it was not yet fully integrated in a precise and coherent geodynamic framework at the scale of the External Rif, in particular, and of the West Mediterranean, in general. We highlight the role of the under-thrusting of the North African margin below the stronger Maghrebian Tethys lithosphere. This under-thrusting is supported by the occurrence of a MP-LT metamorphic gradient shown in the North-Temsamane Units.

Coherently, all the tectonic units initially located in the lower plate of the system (Tafraout-Tifelouest, Senhadja Nappes, MTWs, Prerif) recorded this major event presenting a roughly NW-SE shortening, sealed by the "Mesorif Unconformity". By contrast, units with oceanic affinities (i.e Intrarif-Ketama/Higher nappes & Flyschs Domain), forming the overriding plate, remained unaffected by this deformation. Traces of the North African margin under-thrusting are to be found also eastward in similar structural settings within the external zones of the Western and Central Tell (Algeria) up to Greater Kabylie.

By the Oligocene, the under-thrusting of the North African margin stopped and was relayed by the northward subduction of the Maghrebian Tethys below AlKaPeCa. Hence, since the Miocene, the Rif belt geodynamics is governed by the westward retreat of a wide slab including the Maghrebian Tethys lithosphere and subsequently the African sub-continental lithosphere. At crustal level, this retreat is associated with the exhumation of Temsamane Units and a basement stacking favouring the individualization of the Senhadja nappe. Finally, out-of-sequence deformation gave birth to folding in the Ketama Unit and to the south-westward gravitational emplacement of the Higher Nappes over the whole system. The late stages of the orogenic building are marked by the development of extensional wedge-top basins during the Tortonian. An important kinematic change occurred just after, marked by the recovery of NW-SE shortening directly related to the ongoing Africa-Iberia convergence.

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REFERENCES

Agard, P., Searle, M., Alsop, I., and Dubacq, B. (2010). Crustal stacking and expulsion tectonics during continental subduction: P-T deformation constraints from Oman. Tectonics, 29, TC5018.

Andrieux, J. (1971). La structure du Rif central : étude des relations entre la tectonique de compression et les nappes de glissement dans un tronçon de la chaîne alpine. Notes et Mémoires du Service Géologique, 235.

Azdimousa, A., Bourgois, J., Poupeau, G., Montigny, R. (1998). Histoire thermique du massif de Kétama (Maroc): sa place en Afrique du Nord et dans les Cordillères bétiques. Comptes Rendus de l'Académie des Sciences - Series IIA - Earth and Planetary Science, 326, 847-853.

Azdimousa, A., Bourgois, J., Asebriy, L., Poupeau, G., Montigny, R. (2003). Histoire thermique et surrection du Rif externe et des nappes de flyschs associées (Nord Maroc). Trav. Inst. Sci. Rabat 21, 15–26

Azdimousa, A., Jabaloy-Sánchez, A., Talavera, C., Asebriy, L., González-Lodeiro, F., Evans, N. J. (2019a). Detrital zircon U-Pb ages in the Rif Belt (northern Morocco): Paleogeographic implications. Gondwana Research, 70, 133–150. https://doi.org/10.1016/j.gr.2018.12.008

Azdimousa, A., Jabaloy-Sánchez, A., Münch, P., Martínez-Martínez, J.M., Booth-Rea, G., Vázquez-Vílchez, M., Asebriy, L., Bourgois, J., González-Lodeiro, F.(2019b). Structure and exhumation of the Cap des Trois Fourches basement rocks (eastern Rif, Mo- rocco). Journal of African Earth Sciences 150, 657–672.

Belayouni, H., F. Guerrera, M. Martín-Martín, and F. Serrano (2013), Paleogeographic and geodynamic Miocene evolution of the Tunisian Tell (Numidian and Post-Numidian Successions): bearing with the Maghrebian Chain, *Int J Earth Sci*, *102*(3), 831-855.

Beltrando, M., Rubatto, D., Manatschal, G., 2010b. From passive margins to orogens: The link betweenOcean-Continent Transition zones and (Ultra-)High-Pressure metamorphism. Geology 38, 559–562, doi:10.1130/G30768.1

Beltrando, M., Manatschal, G., Mohn, G., Dal Piaz, G. V., Vitale Brovarone, A., & Masini, E. (2014). Recognizing remnants of magma-poor rifted margins in high-pressure orogenic belts: The Alpine case study. Earth-Science Reviews, 131, 88–115.https://doi.org/10.1016/j.earscirev.2014.01.001

Booth-Rea, G., Jabaloy-Sánchez, A., Azdimousa, A., Asebriy, L., Vázquez-Vílchez, M., Martínez-Martínez, J.M. (2012). Upper-crustal extension during oblique collision: the Temsamane extensional detachment (eastern Rif, Morocco). Terra. Nova, 24, 505–512. https://doi.org/10.1111/j.1365-3121.2012.01089.x.

Bouillin, J.P. (1986). Le «bassin maghrebin»; une ancienne limite entre l'Europe et l'Afrique à l'ouest des Alpes. Bulletin de La Société Géologique de France, 2(4), 547–558.

Bouillin, J. P., Durand-Delga, M., Olivier, P. (1986). Betic-Rifian and Tyrrhenian arcs: distinctive features, genesis and development stages. The origin of arcs, 21, 281-304.

Bulundwe Kitongo, M.K. (1986). Stratigraphie des « sofs » jurassiques du Prérif interne, Maroc: Publications du Département de Géologie et de Paléontologie, Université de Genève, 4, 326.

Capella, W., Matenco, L., Dmitrieva, E., Roest, W.M.J., Hessels, S., Hssain, M., Chakor- Alami, A., Sierro, F.J., Krijgsman, W. (2017). Thick-skinned tectonics closing the Rifian Corridor. Tectonophysics, 710–711, 249–265. http://dx.doi.org/10.1016/j.tecto.2016.09.028.

Capella, W., Barhoun, N., Flecker, R., Hilgen, F. J., Kouwenhoven, T., Matenco, L. C., et al. (2018). Earth-Science Reviews Palaeogeographic evolution of the late Miocene Ri fi an Corridor (Morocco): Reconstructions from surface and subsurface data, 180(February), 37–59. https://doi.org/10.1016/j.earscirev.2018.02.017

Casciello, E., Fernàndez, M., Vergés, J., Cesarano, M., Torne, M. (2015). The Alboran Domain in the Western Mediterranean evolution: the birth of a concept. Bulletin de La Société Géologique de France, 186(4-5), 371– 384.

Chalouan, A., Michard, A., El Kadiri, K., Negro, F., Frizon de Lamotte, D., Soto, J. I., Saddiqi, O. (2008). The Rif belt. In: Michard, A. (Ed.), The Geology of Morocco. Springer, Berlin, 203–302.

Charriere, A. (1990). Héritage hercynien et evolution géodynamique alpine d'une chaîne intracontinentale: le Moyen-Atlas au sud-est de Fès (Maroc), Partie 2, Université Paul Sabatier Toulouse II.

Chazot, G., Abbassene, F., Maury, R.C., Déverchère, J., Bellon, H., Ouabadi, A., et al. (2017). An overview on the origin of post-collisional Miocene magmatism in the Kabylies (northern Algeria): evidence for crustal stacking, delamination and slab detachment. Journal of African Earth Sciences, 125, 27–41.

Chertova, M. V., W. Spakman, A. P. van den Berg, and D. J. J. van Hinsbergen (2014), Absolute plate motions and regional subduction evolution, Geochem Geophy Geosy, 15(10), 3780-3792.

Cifelli, F., Mattei, M., & Porreca, M. (2008). New paleomagnetic data from Oligocene-upper Miocene sediments in the Rif chain (northern Morocco): Insights on the Neogene tectonic evolution of the Gibraltar arc. Journal of Geophysical Research: Solid Earth, 113(2). https://doi.org/10.1029/2007JB005271

Cluzel, D., Aitchison, J .C. and Picard, C. (2001). Tectonic accretion and underplating of mafic terranes in the Late Eocene intraoceanic fore-arc of New Caledonia (Southwest Pacific): geodynamic implications. Tectonophysics, 340, 23-59

Comas, M.C., Platt, J.P., Soto, J.I., Watts, A.B.. (1999). The origin and tectonic history of the Alboran Basin: insights from Leg 161 results. Proceedings of the Ocean Drilling Program Scientific Results, 161, 555–580.

Crespo-Blanc, A., Comas, M., Balanyá, J.C. (2016). Clues for a Tortonian reconstruction of the Gibraltar Arc: structural pattern, deformation diachronism and block rotations. Tectonophysics, 683, 308–324.

D'Acremont, E., Gutscher, M. A., Rabaute, A., Mercier de Lépinay, B., Lafosse, M., Poort, J., et al. (2014). High-resolution imagery of active faulting offshore Al Hoceima, Northern Morocco. Tectonophysics, 632(C), 160–166. https://doi.org/10.1016/j.tecto.2014.06.008

Darraz, C., Leblanc, D., (1989). Interprétation du massif paléozoïque du Khebaba (Rif oriental, Maroc) comme extrusion d'un lambeau de la nappe externe des Senhadja, C. R. Acad. Sci. Paris, 308, 71–74.

Delteil, J. (1974). Tectonique de la chaîne alpine en Algérie d'après l'étude du Tell Oranais oriental, Monts de la Mina, Beni Chougrane, Dahra. Univ. Nice.

Deptuck, M. E., Kendell, K. L. (2017). A Review of Mesozoic-Cenozoic Salt Tectonics Along the Scotian Margin, Eastern Canada. Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins, 287–312. https://doi.org/10.1016/B978-0-12-809417-4.00014-8

De Ruig, M.J. (1992). Tectono-sedimentary Evolution of the Prebetic Fold Belt of Alicante (SE Spain). A Study of Stress Fluctuations and Foreland Basin Deformation. PhD Thesis. Vrije Universiteit, Amsterdam.

Do Couto, D., Gorini, C., Jolivet, L., Lebret, N., Augier, R., Gumiaux, C., et al. (2016). Tectonic and stratigraphic evolution of the Western Alboran Sea Basin in the last 25 Myrs. Tectonophysics, 677, 280– 311

Dodson, M.H., (1973). Closure temperatures in cooling geological and petrological systems, Contrib. Mineral Petrol., 40, 259- 274

Durand Delga, M. (1969). Mise au point sur la structure du Nord-Est de la Berbérie. Publ. Serv. Géol. Algérie, pub. 39, p. 89-131

Durand-Delga, M., Hottinger, L., Marcais, J., Mattauer, M., Milliard, Y., Suter, G. (1960-1962). Donnés actuelles sur la structure du Rif. Mdm. h. s&. Soc. géol. Fr., Livre m6m. Prof. Fallot, 1, 399-422.

Durand-Delga, M., Fontboté, J.M. (1980). Le cadre structural de la Méditerranée occidentale. In 26o Congrès Géol. Intern. Paris, Colloque no. 5, Les chaines alpines issues de la Téthis.

Escosa, F. O., Roca, E., Ferrer, O. (2018). Testing thin-skinned inversion of a prerift salt-bearing passive margin (Eastern Prebetic Zone, SE Iberia). Journal of Structural Geology, 109(February), 55–73. https://doi.org/10.1016/j.jsg.2018.01.004

Et-touhami, M. (2000). Lithostratigraphy and depositional environments of Lower Mesozoic evaporites and associated red beds, KhemissetBasin, northwestern Morocco. Epicontinental Triassic International Symposium.

Fallot, P. (1937). Essai sur la géologie du Rif septentrional. Notes et Mém. Serv. Géol. Maroc. (40) p 553.

Farley, K. A. (2000). Helium diffusion from apatite: General behavior as illustrated by Durango fluorapatite. Journal of Geophysical Research: Solid Earth, 105(B2), 2903-2914.

Farley, K. A., R. A. Wolf, and L. T. Silver (1996), The effects of long alpha-stopping distances on (U-Th)/He ages, Geochim. Cosmochim. Acta, 60(21), 4223–4229.

Faure-Muret, A., Choubert, G. (1971). Le Maroc. Domaine rifain et atlasique. In: UNESCO (Ed.), Tectonique de l'Afrique. Sci. Terre 6, pp. 17–46.

Favre, P. (1992). Géologie des massifs calcaires situés au front S de l'unité de Kétama (Rif, Maroc). Publications du Département de Géologie et Paléontologie, Univ. Genève, 11, 138.

Favre, P., Stampfli, G., Wildi, W. (1991). Jurassic sedimentary record and tectonic evolution of the northwestern corner of Africa. Palaeogeography, Palaeoclimatology, Palaeoecology, 87, 53-73.

Fedan, B., (1988). Evolution géodynamique d'un bassin intraplaque sur décrochements: le Moyen Atlas durant le Méso-Cénozoique, Trav. Inst. Sci. Rabat, 141.

Fenet, B. (1975). Recherches sur l'alpinisation de la bordure septentrionale du bouclier africain : à partir de l'étude d'un élément de l'Orogène nord-maghrébin : les Monts du Djebel Tessala et les Massifs du littoral oranais. Nice, France: Univ. Nice.

Fenet B, Macoin P, Magne J. 1969. Mise en evidence d'une phase tectonique intra-lutetienne dans l'unité de Sidi el Hadri (monts du Tessala, Algerie occidentale). Bulletin de La Société Géologique de France 7(6): 904–908.

Flinch, J.F. (1994). Tectonic evolution of the Gibraltar Arc. Houston, Texas, US: Rice University.

Flinch, J., Soto, J. (2017). Allochthonous Triassic and Salt TectonicProcesses in the Betic-Rif Orogenic Arc. In: SOTO, J.I., FLINCH, J.F. & TARI, G. (eds) Permo-Triassic Salt Provinces of Europe, North Africa and the Central Atlantic: Tectonics and Hydrocarbon Potential. Elsevier, Amsterdam, 243–261. https://doi.org/10.1016/B978-0-12-809417-4.00020-3

Flowers, R.M., Ketcham, R.A., Shuster, D.L., Farley, K.A., (2009). Apatite (UeTh)/He thermochronometry using a radiation damage accumulation and annealing model. Geochem. Cosmochim. Acta 73, 2347-2365.

Frets, E.C., Tommasi, A., Garrido, C.J., Vauchez, A., Mainprice, D., Targuisti, K., Amri, I. (2014). The Beni-Bousera peridotite (Rifbelt, Morocco): an oblique-slip low-angle shear zone thinning the subcontinental mantle lithosphere. J. Petrol. 55 (2), 283–313.

Frizon de Lamotte, D. (1981). L'olistostrome Tortonien du Nékor et le probléme de l'origine du matériel allochtone du Rif externe Bull. Soc. géol. Fr. (7), XXIII, 419--427.

Frizon de Lamotte, D. (1982). Contribution à l'etude de l'evolution structurale du Rif oriental (Maroc). Notes et Mémoires du Service Géologique. Rabat, Morocco: Service géologique du Maroc. 314, 239-309.

Frizon de Lamotte, D. (1985). La structure du Rif oriental (Maroc). Rôle de la tectonique longitudinale et importance des fluides. These Doct. Etat, Univ. P. et M. Curie, Paris VI; Sci. Terre Univ. P. et M. Curie n ° 85-03.

Frizon de Lamotte, D. (1987). Un exemple de collage synmétamorphe: la déformation miocene des Temsamane (Rif, Maroc). Bull. Soc. Géol. Fr. (8), III, 337-344.

Frizon de Lamotte, D. (1987b). La structure du Rif externe (Maroc): mise au point sur le rôle des décrochements des chevauchements et des glissements gravitaires. Journal of African Earth Sciences, 6(5), 7555–7766. Retrieved from files/2340/Frizon de Lamotte - 1987 - La structure du Rif externe (Maroc) mise au point.pdf

Frizon de Lamotte, D., Leikine, M. (1985). Métamorphisme miocène du Rif oriental (Maroc) et individualisation de la nappe gravitaire d'Aknoul. Rev. Géologie Dyn. Géographie Phys. 26, 29–42.

Frizon de Lamotte, D., Andrieux, J., Guezou, J. C. (1991). Cinématique des chevauchements néogènes dans l'Arc bético-rifain: discussion sur les modèles géodynamiques, Bull. Soc. Géol. Fr. 169, 611–626.

Frizon de Lamotte, D., Leturmy, P., Missenard, Y., Khomsi, S., Ruiz, G., Saddiqi, O., Guillocheau, F., Michard, A. (2009). Mesozoic and Cenozoic vertical movements in the Atlas system (Algeria, Morocco, Tunisia): an overview. Tectonophysics, 475(1), 9-28.

Frizon de Lamotte, D., Raulin, C., Mouchot, N., Wrobel-Daveau, J. C., Blanpied, C., Ringenbach, J. C. (2011). The southernmost margin of the Tethys realm during the Mesozoic and Cenozoic: Initial geometry and timing of the inversion processes. Tectonics, 30, TC3002. https://doi:10.1029/2010TC002691

Frizon de Lamotte, D., Saint Bezar, B., Bracène, R., Mercier, E. (2000). The two main steps of the Atlas building and geodynamics of the western Mediterranean. Tectonics, 19(4), 740-761.

Frizon de Lamotte, D., Zizi, M., Missenard, Y., Hafid, M., Azzouzi, M.E., Maury, R.C., Charrière, A., Taki, Z., Benammi, M. and Michard, A. (2008). The Rif Belt Continental Evolution, In: Michard, A. et al. (Eds.), The Geology of Morocco, Springer Berlin / Heidelberg, 116, 133-203.

Galindo-Zaldívar, J., Azzouz, O., Chalouan, A., Pedrera, A., Ruano, P., Ruiz-Constán, A., et al. (2015). Extensional tectonics, graben development and fault terminations in the eastern Rif (Bokoya-Ras Afraou area). Tectonophysics, 663, 140–149. https://doi.org/10.1016/j.tecto.2015.08.029

Galbraith, R.F., Laslett, G.M., (1993). Statistical models for mixed fission track ages. Nucl. Tracks, 21, 459–470.

Gallagher, K. (2012). Transdimensional inverse thermal history modeling for quantitative thermochronology. J. Geophys. Res. Solid Earth 117 (B2).

García-Hernández, M., López-Garrido, A.C., Rivas, P., Sanz de Galdeano, C., and Vera, J.A. (1980). Mesozoic palaeogeographic evolution of the External Zones of the Betic Cordillera. Geologie en Mijnbouw, 59, 155-168.

Gautheron, C.E., Tassan-Got, L., Barbarand, J. & Pagel, M.(2009) Effect of alpha-damage annealing on Apatite (U-Th)/He thermochronology. Chem. Geol., 266, 166–179.

Gautheron C. and Tassan-Got L. (2010) A Monte Carlo approach to diffusion applied to noble gas/helium thermochronology. Chemical geology 273(3-4), 212-224.

Gautheron, C., Tassan-Got, L., Ketcham, R. A., & Dobson, K. J. (2012). Accounting for long alpha-particle stopping distances in (U–Th–Sm)/He geochronology: 3D modeling of diffusion, zoning, implantation, and abrasion. Geochimica et Cosmochimica Acta, 96, 44-56.

Gimeno-Vives, O., Mohn, G., Bosse, V., Haissen, F., Zaghloul, M. N., Atouabat, A., Frizon de Lamotte, D. (2019). The Mesozoic margin of the Maghrebian Tethys in the Rif belt (Morocco): Evidence for poly-phase rifting and related magmatic activity. Tectonics, 21, 9289. https://doi.org/10.1029/2019tc005508

Gimeno-Vives, O., Mohn, G., Bosse, V., Haissen, F., Zaghloul, M. N., Atouabat, A., & Frizon de Lamotte, D. (2020).Reply to comment by Michard et al. on "The Mesozoic margin of the Maghrebian Tethys in the Rif Belt (Morocco): Evidence for polyphase rifting and related magmatic activity". Tectonics, 38. https://doi.org/10.1029/ 2020TC006165

Gleadow, A. J. W.,& Duddy, I. R. (1981). A natural long-term track annealing experiment for apatite. Nuclear Tracks, 5(1-2), 169–174.

Gleadow, A. J. W., Duddy, I. R., Green, P. F., & Lovering, J. F. (1986). Confined fission track lengths in apatite: a diagnostic tool for thermal history analysis. Contributions to Mineralogy and Petrology, 94(4), 405–415. https://doi.org/10.1007/BF00376334

Green, P.F. (1981). A new look at statistics in fission track dating. Nucl. Tracks, 5, 76-86

Guenthner, W. R., P. W. Reiners, R. A. Ketcham, L. Nasdala, and G. Giester. (2013). Helium diffusion in natural zircon: Radiation damage, anisotropy, and the interpretation of zircon (U-Th)/He thermochronology, Am. J. Sci., 313(3), 145–198.

Guardia, P. (1975). Géodynamique de la marge alpine du continent africain d'après l'étude de l'Oranie nord-occidentale: relations structurales et paléogéographiques entre le Rif externe, le Tell et l'avant-pays atlasique. Nice, France: Univ. Nice.

Guerrera, F., Martín-Martín, M., Perrone, V., Tramontana, M. (2005). Tectono-sedimentary evolution of the southern branch of the Western Tethys (Maghrebian Flysch Basin and Lucanian Ocean): consequences for Western Mediterranean geodynamics. Terra Nova, 17(4), 358–367.

Guerrera, F., Martín-Algarra, A., Martín-Martín, M. (2012). Tectono-sedimentary evolution of the "Numidian Formation" and Lateral Facies (southern branch of the western Tethys): constraints for central-western Mediterranean geodynamics. Terra Nova 24, 3–41.

Gueydan, F., Pitra, P., Afiri, A., Poujol, M., Essaifi, A., Paquette, J.-L., 2015. Oligo-Miocene thinning of the Beni Bousera peridotites and their Variscan crustal host rocks, Internal Rif, Morocco. Tectonics 34, 1244–1268. https://doi.org/10.1002/2014TC003769.

Guillemin, M., Houzay, J.P. (1982). Le Néogène post-nappes et le Quaternaire du Rif Nord oriental. Stratigraphie et tectonique des bassins de Melilla, de Kert, de Boudinar et du piémont des Kebdana. Notes & Mém. Serv. géol. Maroc, 314, 7-239

Hafid, M., Tari, G., Bouhadioui, D., Moussaid, I. E., Echarfaoui, H., Salem, A. A., et al. (2008). Atlantic basins. In A. Michard, O. Saddiqi, A. Chalouan, & D. Frizon de Lamotte (Eds.), Structure, Stratigraphy and Tec- tonics of the Africa–Atlantic–Mediterranean Triple Junction. Lecture Notes in Earth Sciences (Vol. 116, pp. 303–329). https://doi.org/10.1007/978-3-540-77076-3_6

Handy, M.R., Schmid, S.M., Bousquet, R., Kissling, E., Bernoulli, D. (2010). Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps. Earth-Science Reviews, 102(3), 121-158.

Hervouet, Y. (1985). Géodynamique alpine (Trias-Actuel) de la marge septentrionale de l'Afrique au Nord du bassin de Guercif. Thése. Sc. Pau

Hervouet, Y. et de Luca, P. (1980). Place de l'unité chaotique de Gareb-Kebdana dans l'orogène rifain, implications géo- dynamiques. Bull. Soc. gèol. Fr. (7), XXII, 305-310.

Hurford, A.J., Green, P.F. (1983). The zeta age calibration of fission-track dating. Chem. Geol. 41, 285–317

Jabaloy-Sánchez, A., Azdimousa, A., Booth-Rea, G., Asebriy, L., Vazquez-Vilchez, M., Miguel Martinez-Martinez, J., Gabites, J. (2015). The structure of the Temsamane fold- and-thrust stack

(eastern Rif, Morocco): evolution of a transpressional orogenic wedge. Tectonophysics, 663, 150–176.

Jolivet, L., Faccenna, C. (2000). Mediterranean extension and the AfricaEurasia collision. Tectonics, 19(6), 1095–1106.

Jolivet, L., Augier, R., Faccenna, C., Negro, F., Rimmele, G., Agard, P., et al. (2008). Subduction, convergence and the mode of backarc extension in the Mediterranean region. Bulletin de la Société Géologique de France, 179(6), 525–550.

Ketcham, R. A. (2005). Forward and inverse modeling of low-temperature thermochronometry data. Reviews in mineralogy and geochemistry, 58(1), 275-314.

Ketcham, R.A., Gautheron, C., Tassan-Got, L. (2011). Accounting for long alpha- particle stopping distances in (U-Th-Sm)/He geochronology: refinement of the baseline case. Geochem. Cosmochim., 75, 7779-7791.

Khomsi, S., M. G. Ben Jemia, D. Frizon de Lamotte, C. Maherssi, O. Echihi, and R. Mezni. (2009). An overview ofthe Late Cretaceous–Eocene positive inversions and Oligo-Miocene subsidence events in the foreland of the Tunisian Atlas: Structural style and implications for the tectonic agenda of the Maghrebian Atlas system, Tectonophysics, 475,38–58, doi:10.1016/j.tecto.2009.02.027.

Khomsi, S., Frizon de Lamotte, D., Bédir, M., Echihi, O. (2016). The Late Eocene and Late Miocene fronts of the Atlas Belt in eastern Maghreb: Integration in the geodynamic evolution of the Mediterranean Domain. Arabian Journal of Geosciences, 9(15), 650

Koulali, A., Ouazar, D., Tahayt, A., King, R.W., Vernant, P., Reilinger, R.E., McClusky, S., Mourabit, T., Davila, J.M., and Amraoui, N. (2011). New GPS constraints on active deformation along the Africa–Iberia plate boundary. Earth and Planetary Science Letters, 308(1–2), 211-217.

Laffitte, R. (1939). Étude géologique de l'Aurès [Algérie]. Service de la carte géologique de l'Algérie.

Lagabrielle, Y., Chauvet, A., Ulrich, M., & Guillot, S. (2013). Passive obduction and gravity-driven emplacement of large ophiolitic sheets: TheNew Caledonia ophiolite (SW Pacific) as a case study? Bulletin de la Société Géologique de France, 184(6), 545–556.

Leblanc, D. (1979). Etude geologique du Rif externe oriental au Nord de Taza (Maroc). Notes et Mdm. Serv. gdol. Maroc, Rabat, 281.

Leblanc, D. (1983). Carte géologique du Rif, feuille de Taïneste au 1/50.000. Notes et Mémoires du Service géologique du Maroc, 305.

Leblanc, D., Feinberg, H. (1982). Nouvelles données stratigraphiques et structurales sur le Numidien du Rif oriental (Maroc). Implications géodynamiques, Bull. Soc. Géol. Fr. (7), 24, 861–865.

Leblanc, D., Olivier, P. (1984). Role of strike-slip faults in the Betic-Rifian Orogeny. Tectonophysics, 101, 345-355.

Leikine, M., Asebriy, L. et Bourgois, J. (1991). Sur l'age du metamorphisme anchi-epizonal de l'unite de Lack of low-grade metamorphism in the Triassic formations of the Argana basin 573 Ketama, Rif Central (Maroc). Comptes Rendus Acadkrnies Sciences, 313, 787-793.

Leprêtre, R. (2015). Evolution phanérozoïque du Craton Ouest Africain et de ses bordures Nord et Ouest. Univ. Paris-Sud Saclay.

Leprêtre, R., Missenard, Y., Barbarand, J., et al. (2015) Post-Rift History of the Eastern Central Atlantic Passive Margin: Insights from the Saharan Region of South Morocco. Journal of Geophysical Research: Solid Earth, 120, 4645-4666.https://doi.org/10.1002/2014JB011549

Leprêtre, R., Frizon de Lamotte, D., Combier, V., Gimeno-Vives, O., Mohn, G., Eschard, R. (2018). The Tell-Riforogenic system (Morocco, Algeria, Tunisia) and the structural heritage of the southern Tethys margin, BSGF. Earth Sciences Bulletin, 18, 10.

Levy, R. G., Tilloy, R. (1952). Maroc septentrional (chaine du Rif), partie B.Livret-guide de excursions A31 et C31. Congres Geologique International, XIX session, Ager, serie Maroc, 8, 65.

Lonergan, L., White, N. (1997). Origin of the Betic-Rif mountain belt. Tectonics, 16(3), 504-522.

Lujan, M., A. Crespo-Blanc, and J. C. Balanya (2006), The Flysch Trough thrust imbricate (Betic Cordillera): A key element of the Gibraltar Arc orogenic wedge, *Tectonics*, *25*(6).

Malusà, M. G., and Fitzgerald, P. G., eds (2019). Fission-Track Thermochronology and its Application to Geology(393 pp). Springer.

Mancilla, F.L., Stich, D., Morales, J., Julià, J., Diaz, J., Pazos, A., Córdoba, D., Pulgar, J.A., Ibarra, P., Harnafi, M., Gonzalez-Lodeiro, F. (2012). Crustal thickness variations in northern Morocco. J. Geophys. Res. 117, B02312. https://doi.org/10.1029/ 2011JB008608.

Mancilla, F. L., Stich, D., Berrocoso, M., Martín, R., Morales, J., Fernandez-Ros, A., Páez, R., and Pérez-Peña, A. (2013). Delamination in the Betic Range: Deep structure, seismicity, and GPS motion. Geology, 41, 307-310.

Mancilla, F. L., Diaz, J. (2015). High resolution Moho topography map beneath Iberia and Northern Morocco from receiver function analysis. Tectonophysics 663, 203-211. doi:10.1016/j.tecto.2015.06.017

Mattauer, M. (1958). Étude géologique de l'Ouarsenis oriental. Publ. Serv. Carte Géol. Algérie, Nouv. Ser., Bull (17). Alger: Service de la carte géologique de l'Algérie

Mauffret, A., Frizon de Lamotte, D., Lallemant, S., Gorini, C., and Maillard, A. (2004). E–W opening of the Algerian Basin (Western Mediterranean). Terra Nova, 16, 257-264.

Michard, A. (2015). Géologié du Rif , à l'éxtrémité occidéntàlé dé là chàîné àlpiné. 1–20.

Michard, A., Feinberg, H., El-Azzab, D., Bouybaouène, M., Saddiqi, O. (1992). A serpentinite ridge in a collisional paleomargin setting; the Beni Malek Massif, external Rif, Morocco. Earth and Planetary Science Letters, 113(3), 435–442.

Michard, A., Negro, F., de Lamotte, D. F., Saddiqi, O. (2007). Serpentinite slivers and metamorphism in the External Maghrebides: arguments for an intracontinental suture in the African paleomargin (Morocco, Algeria). Rev. Soc. Geol. España, 20(3–4), 173-185.

Michard, A., Mokhtari, A., Chalouan, A., Saddiqi, O., Rossi, P., Rjimati, E. C. (2014). New ophiolite slivers in the External Rif belt, and tentative restoration of a dual Tethyan suture in the western Maghrebides. Bull. Soc. Geol. Fr., 185, 313–328.

Michard, A., Chalouan, A., Negro, F., & Saddiqi, O. (2015). Comment on "Evidence of extensional metamorphism associated to Cretaceous rifting of the North-Maghrebian passive margin: The tanger-ketama unit (external rif, Northern Morocco)" by Vázquez et al., geologica acta 11 (2013), 277-293. Geologica Acta, 13(1), 69–76. https://doi.org/10.1344/GeologicaActa2015.13.1.5

Michard, A., Mokhtari, A., Lach, P., Rossi, P., Chalouan, A., Saddiqi, O., & Rjimati, E. C. (2018). Liassic age of an oceanic gabbro of the External Rif (Morocco): Implications for the Jurassic continent–ocean boundary of Northwest Africa. Comptes Rendus Geoscience, 350(6), 299–309. https://doi.org/10.1016/j.crte.2018.05.006

Monié, P., Frizon de Lamotte, D., Leikine, M. (1984). Étude géochronologique préliminaire par la méthode Ar/Ar du métamorphisme alpin dans le Rif externe (Maroc). Précisions sur le calendrier tectonique tertiaire. Revue de Geographie Physique et de Geologie Dynamique, 25(4), 307–317.

Morel, J.L. (1980). Contribution à l'étude géologique et structurale de la région de Midar (Rif Oriental, Maroc). Thése de 3éme cycle. Université Paris Sud, Orsay, 177.

Morel, J.L. (1988) Evolution recente de l'orogene rifain et de son avant pays depuis la fin de la mise en place des nappes (Rif- Maroc). Mem Geodiffusion 4:584

Muñoz, J. A. (1992). Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced crosssection. . Springer Netherlands. Thrust tectònics, 235-246.

Negro, F., Agard, P., Goffé, B., Saddiqi, O. (2007). Tectonic andmetamorphic evolution of the Temsamane units, External Rif (northern Morocco): implications for the evolution of the Rif and the Betic–Rif arc. J. Geol. Soc. Lond., 164, 829–842.

Negro, F., De Sigoyer, J., Goffé, B., Saddiqi, O., Villa, I.M. (2008). Tectonic evolution of the Betic-Rif arc: new constraints from 40 Ar/39 Ar dating on white micas in the Temsamane units (External Rif, northern Morocco). Lithos, 106(1), 93–109

Nocquet, J. M. (2012). Present-day kinematics of the Mediterranean: A comprehensive overview of GPS results. Tectonophysics, 579, 220–242. https://doi.org/10.1016/j.tecto.2012.03.037

Papillon, R. (1989). Stratigraphie des Sofs Lias-Dogger des massifs des Senhadja et de l'Azrou Akchar (Rif, Maroc). Publications duDépartement Géologie et de Paléontologie de l'Université de Genève, 8, 217.

Patriat, M., Collot, J., Etienne, S., Poli, S., Clerc, C., Mortimer, N., et al. (2018). New Caledonia Obducted Peridotite Nappe: Offshore Extent and Implications for Obduction and Postobduction Processes. Tectonics, 37(4), 1077–1096. https://doi.org/10.1002/2017TC004722

Pérouse, E., Vernant, P., Chéry, J., Reilinger, R., McClusky, S. (2010). Active surface deformation and sub-lithospheric processes in the western Mediterranean constrained by numerical models. Geology, 38(9), 823–826.

Petit, C., Le Pourhiet, L., Scalabrino, B., Corsini, M., Bonnin, M., Romagny, A. (2015). Crustal structure and gravity anomalies beneath the Rif, northern Morocco: Implications for the current tectonics of the Alboran region. Geophysical Journal International, 202(1), 640–652. https://doi.org/10.1093/gji/ggv169

Platt JP, WhitehouseMJ, Kelley SP, Carter A, Hollick L. (2003). Simultaneous extensional exhumation across the Alborán Basin: implications for the causes of late-orogenic extension. Geology 31:259–62

Platt, J.P., Behr, W.M., Johanesen, K., Williams, J.R. (2013). The Betic-Rif arc and its orogenic hinterland: a review. Annual Review of Earth and Planetary Sciences, 41, 313–357.

Ricou, L.E. (1994). Tethys reconstructed: paltes, continental frragments and their Boundaries since 260 Ma from Central America to South-eastern Asia. Geodinamica Acta, 7(4), 169-218.

Roca, E., Guimera, J. (1992). The Neogene structure of the eastern Iberian margin: structural constraints on the crustal evolution of the Valencia Trough (western Mediterranean). Tectonophysics, 203, 203-218

Romagny, A., Münch, P. H., Cornée, J. J., Corsini, M., Azdimousa, A., Melinte-Dobrinescu, M. C., Ben Moussa, A. (2014). Late Miocene to present-day exhumation and uplift of the Internal Zone of the Rif chain: Insights from low temperature thermochronometry and basin analysis. Journal of Geodynamics, 77, 39–55. https://doi.org/10.1016/j.jog.2014.01.006

Rossetti, F., Lucci, F., Theye, T., Bouybaouenne, M., Gerdes, A., Opitz, J., et al. (2020). Hercynian anatexis in the envelope of the Beni Bousera peridotites (Alboran Domain, Morocco): Implications for the tectono-metamorphic evolution of the deep crustal roots of the Mediterranean region. Gondwana Research, 83, 157–182. https://doi.org/10.1016/j.gr.2020.01.020

Royden, L., & Faccenna, C. (2018). Subduction Orogeny and the Late Cenozoic Evolution of the Mediterranean Arcs. Annual Review of Earth and Planetary Sciences, 46(1), 261–289. https://doi.org/10.1146/annurev-earth-060115-012419

Samaka, F., Benyaich, A., Dakki, M., Hçaine, M., Bally, A.W. (1997). Origine et inversion des bassins miocènes supra- nappes du Rif Central (Maroc). Etude de surface et de subsurface. Exemple des bassins de Taounate et de Tafrannt. Geodinamica Acta, 10, 30-40

Schmid, S. M., Pfiffner, O. A., Froitzheim, N., Schönborn, G., & Kissling, E. (1996). Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. Tectonics, 15(5), 1036–1064. https://doi.org/10.1029/96TC00433.

Shuster D. L., Flowers R. M., Farley K. A. (2006). The influence of natural radiation damage on helium diffusion kinetics in apatite. Earth and Planetary Science Letters, 249, 148–161.

Soto, J. I., Flinch, J., and Tari, G. (2017). Permo-Triassic salt provinces of Europe, North Africa and the Central Atlantic: Tectonics and hydrocarbon potential (pp. 243–261). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-809417-4.00038-0

Suter, G. (1965). La région du Moyen Ouen-ha (Rif, Maroc). Etude préliminaire sur la stratigraphie et la tectonique. Notes Mém. Serv. Géol. Maroc, 183, 7-17.

Suter, G. (1980a). Carte geologique de la chaine rifaine a 1/500 000. Notes et Mdm. Serv. geol. Maroc, n ° 245a.

Suter, G. (1980b). Carte structurale de la chaine rifaine h 1/500000. Notes et Mdm. Serv. geol. Maroc, n ° 245b.

Tari, G., Novotny, B., Jabour, H., Hafid, M. (2017). Salt Tectonics Along the Atlantic Margin of NW Africa (Morocco and Mauritania). In: SOTO, J.I., FLINCH, J.F. & TARI, G. (eds) Permo-Triassic Salt Provinces of Europe, North Africa and the Central Atlantic: Tectonics and Hydrocarbon Potential. Elsevier, Amsterdam, 243–261. https://doi.org/10.1016/B978-0-12-809417-4.00016-1

Van Hinsbergen, D.J.J., Vissers, R.L.M., Spakman, W. (2014). Origin and consequences of western Mediterranean subduction, rollback, and slab segmentation. Tectonics, 33, 393–419.

Van Hinsbergen, D. J. J., Torsvik, T. H., Schmid, S. M., Maţenco, L. C., Maffione, M., Vissers, R. L. M., et al. (2020). Orogenic architecture of the Mediterranean region and kinematic reconstruction of its tectonic evolution since the Triassic. Gondwana Research, 81, 79–229. https://doi.org/10.1016/j.gr.2019.07.009

Vázquez, M., Asebriy, L., Azdimousa, A., Jabaloy, A., Booth-Rea, G., Barbero, L., Mellini, M., González-Lodeiro, F. (2013). Evidence of extensional metamorphism associated to Cretaceous rifting of the north-Maghrebian passive margin: the Tanger–Ketama unit (external Rif, northern Morocco). Geol. Acta 11, 277–293.

Vera, J.A., Molina, J.M., Aguado, R., 2004. Calcarenitas de Microcodium (Formación Majalcorón, Paleoceno, Subbético): descripción, bioestratigrafía y significado en el Terciario de la Cordillera Bética. Bol. Geológico Min. Esp. 115, 453–468.

Vergés, J., Millan, H., Roca, E., Muñioz, J. A., and Marzo, M. (1995). Eastern Pyrenees and related foreland basins: Pre-, syn-and post-collisional crustal-scale cross-sections. Marine and Petroleum Geology, 12(8), 903–915. https://doi.org/10.1016/0264-8172(95)98854-X

Vergés J, Sàbat F. (1999). Constraints on the Neogene Mediterranean kinematic evolution along a 1000 km transect from Iberia to Africa. Geological Society, London, Special Publications 156(1): 63–80.

Vergés, J., Fernàndez, M., Martínez, A., 2002. The Pyrenean orogen: pre-, syn-, and postcollisional evolution. Journal of the Virtual Explorer 08, 55–74.

Vergés, J., Fernàndez, M. (2012). Tethys-Atlantic interaction along the Iberia–Africa plate boundary: The Betic-Rif orogenic system. Tectonophysics, 579, 144–172.

Vermeesch, P. (2007). Quantitative geomorphology of the White Mountains (California) using detrital apatite fission track thermochronology. Journal of Geophysical Research: Earth Surface, 112(F3)

Vila, J.M. (1980). La chaîne alpine d'Algérie orientale et des confins algéro-tunisiens. Université Paris-VI, Pierre et Marie Curie.

Vila, J.M, Ben Youssef, M., Chikhaoui, M., Ghanmi, M. (1996). Un grand "glacier de sel" sous marin albien de Tunisie du Nord-Ouest: exemple du secteur minier de Gueurn Halfaya. C.R.Acad. Sci. Paris, 327, pp. 563-570.

Vila, J.M, Ben Youssef, M., Chikhaoui, M., Ghanmi, M., Kassii, S., Miaadi, F. (1998). Tectonique en radeaux au toit d'un "glacier de sel" sous marin albien du Nord-Ouest tunisien (250km2?): le matériel salifère triassique du "diapir2 de ben Gasseur et de l'anticlinal d'El Kef. C.R.Acad. Sci. Paris, 322, pp. 221-227.

Vidal, J. C. (1977). Structure actuelle et évolution depuis le Miocène de la chaîne rifaine partie sud de l'Arc de Gibraltar. Bulletin de la Société géologique de France, 19 (7), 789–796.

Vidal, J. C. (1983). Carte géologique du Rif, feuille de Dhar Souk au 1/50.000. Notes et Mémoire du Service géologique du Maroc, 298.

Vitale, S., Zaghloul, M.N., Tramparulo, F.D.A., El Ouaragli, B. (2014). Deformation characterization of a regional thrust zone in the northern Rif (Chefchaouen, Morocco). J. Geodyn. 77, 22–38.

Wernli R. (1987). Micropaléontologie du Néogène post-nappes du Maroc septentrional et description syst´ematique des foraminif`eres planctoniques, Notes M´em. Serv. géol. Maroc, 331, 1– 266.

Wildi, W. (1981). Le Ferrysch: cône de sédimentation détritique en eau profonde à la bordure nord-ouest de l'Afrique au Jurasique moyen à supérieur (Rif externe, Maroc). Eclogae Geologiae Helvetiae, 74, 481–527.

Wildi, W. (1983). La chaıne tello-rifaine (Algérie, Maroc, Tunisie): structure, stratigraphie et évolution du Trias au Miocène. Rev. Geol. Dyn. Geogr. Phys., 24, 201–297.

Wolf, R. A., Farley, K. A., and Silver, L. T. (1996). Helium diffusion and low-temperature thermochronometry of apatite. Geochimica et Cosmochimica Acta, 60(21), 4231-4240.

Wortel, M. J. R., and Spakman, W. (2000). Subduction and slab detachment in the Mediterranean-Carpathian region. Science, 290(5498), 1910-1917.

Wrobel-Daveau, J.-C., Ringenbach, J.-C., Tavakoli, S., Ruiz, G. M. H., Masse, P., & Frizon de Lamotte, D. (2010). Evidence for mantle exhumation along the Arabian margin in the Zagros (Kermanshah

area, Iran). Arabian Journal of Geosciences, 3(4), 499–513. https://doi.org/10.1007/s12517-010-0209-z

Zaghloul, M.N., Staso, A.D., Hlila, R., Perrone, V., Perrotta, S., (2010). The Oued Dayr formation: first evidence of a new Miocene late-orogenic cycle on the Ghomaride Complex (Internal domains ofthe Rifian Maghrebian Chain, Morocco). Geodin. Acta, 23, 185–194

Zizi, M. (2002). Triassic-Jurassic extensional systems and their Neogene reactivation in Northern Morocco: the Rides Prerifaines and Guercif Basin. In: Notes et Mémoires du Service Géologique, 416.

Figure captions

Fig 1. (a) Structural map of the Rif belt in North Morocco (modified after Suter 1980b; Chalouan et al., 2008). The principal tectonic units are shown with special emphasis on the External Rif. The location of the figures 2, 3, 5 and 9 are indicated. (b) Unified map of the Betic-Rif-Tell orogen (modified after Leprêtre et al., 2018).

Fig 2. Detailed structural map of the Central and Eastern External Rif. Map compiled from the Geological map of the Rif at 1/500 000 by G. Suter 1980 and the Geological maps of the Rif at 1/50 000 published by the Geological Survey of Morocco (names of the map: Al Hoceima, Boudinar, Kebdani, Midar, Moyen Ouergha, Dhar souk, Taineste, Aknoul, Beni Frassene and Taza), the Geological map of the Central Rif by J. Andrieux (1971) and unpublished mapping by D. Frizon de Lamotte (Tizi Ousli sheet in particular) and the authors of the present paper. The outcrops described in the text are located on the map. The marks of lineation are from the literature (a. Andrieux, 1971; b. Frizon de Lamotte, 1985, 1987; Jabaloy-Sánchez et al., 2015). Red dots indicate the places where the Oligocene-Miocene is paleontologically dated (Vidal, 1977; Leblanc, 1979; Frizon de Lamotte, 1985; Favre, 1992). MTW: "Mesorif Tectonic Window"; B.H :Bou Haddoud Nappe; J. Jebel and B.: Basin.

Fig 3. Geological cross-sections through the External Rif (see location in figure 1 and 2) based on existing geological maps, subsurface data and own work. (a) Section from the Ketama unit to the Eastern Foreland crossing the Temsamane massif; (b) Section from the Flyschs Units to the Eastern Foreland, crossing the Azrou Akchar Massif and the Jebel Berkane; (c) Section from the Flyschs Units to the Middle Atlas, crossing the Tifelouest-Tafraout Unit the Senhadja Nappe and the Tamda Tectonic Window.

Fig. 4. Stratigraphic chart of the External Rif structural units and Foreland domains. The chart highlights the position of the Mesorif unconformity, and the trajectories of the main thrust-faults (Senhadja Nappes in blue and Higher Nappes in orange).

Fig. 5. Panoramic view of contact between the Tazzeka Paleozoic Massif (Middle Atlas) and the Rif Belt (see location on Fig. 1). The Upper Miocene sediments of the foredeep rest directly over the Paleozoic of the Foreland with a strong unconformity in between. A Higher Nappes (Tsoul Unit in this case) is overthrusting the Miocene of the foredeep through a very flat thrust-fault.

Fig. 6. Schematic without scale cross-sections illustrating the structural position of the main units of the External Rif along: (a) the Central Rif (Tamda Tectonic Window) and (b) the Eastern Rif (Temsamane Units). The blue thrust-fault underlines the floor of the Senhadja Nappe (S.N. floor thrust); the orange thrust-fault the floor of the Higher Nappes (H.N. floor thrust), but also (section b) elements of Senhadja. The sequence of deformation/thrusting is globally break-back

(from the external to the internal) in the following order: (1) shortening in the MTWS (sealed by the Mesorif Unconformity) (2) emplacement of Senhadja and (3) emplacement of the Higher Nappes. A late (Tortonian) collapse allows the development of the wedge-top basins. It is followed by a Late Tortonian-to-Present contraction (section a).

Fig. 7: (a) Panoramic view of the Tamda Tectonic Window (See location in Fig. 2); (b) Geological interpretation of the panoramic view. Note the Mesorif unconformity, the Miocene sediments (conglomerates, marls) and the Senhadja Nappes on top; (c) Close up view of the deformed Mesozoic sequence of the Tamda Tectonic Window with the Mesorif unconformity and Miocene sediments on top; (d) Close up view of the Senhadja Nappe with Jurassic carbonates overlaying the Miocene of the Tamda Window. Red dot indicates the place where the Lower Miocene has been paleontologically dated (Vidal, 1977)

Fig. 8. Photos illustrating the style of deformation in the North Temasamane Units. (a) Fold in the Ras Afraou quartzite (see location on Fig. 2); (b) Superimposed folding and cleavage development in Mesozoic calcareous schales of the North Temsamane Massif.

Fig. 9. Detailed structural-geological maps of (a) the Senhadja Nappe s.s and (b) the metamorphic Senhadja Nappe(See location on Figs. 1 and 2). The maps illustrate the structural position of the Nappe (on top of the Mesorif Tectonic Windows and below the Higher Nappes) and its apparent chaotic internal structure.

Fig. 10. Recumbent fold in the Neocomian calcareous shales of the Ketama Unit (Oued Timerzga; see location on Fig. 2).

Fig. 11. (a) View of the Jebel Berkane northern flanck (Aknoul Nappe, see location on Fig. 2) showing the poor deformation within the Aknoul Nappe (bedding is flat);(b) Close up view of the transition from Paleocene black shales to Lower Eocene limestone.

Fig. 12. View a former salt canopy preserved within the Cretaceous dark marls of the Aknoul Nappe (Location on Fig. 2).

Fig. 13. Map of the Upper Miocene wedge-top basins of the Eastern and Central Rif. Note the counter-clockwise vertical axis rotation recorded by paleomagnetism in the Central Rif basins (from Cifelli et al., 2008). It is consistent with the persistence of left-lateral movement along the Nekor Fault Zone during and after the uppermost Miocene. By contrast no rotation is recorded in the Boudinar Basin (Eastern Rif).

Fig. 14. Thermal modeling results for samples RE-27 and RE-47. (a) Thermal history of sample RE-27 Bou Adel sample. LogLikelihood = -159.84 (See Gallagher, 2012 for further details). (b) Thermal history for sample RE-47 Jebel Baïo; LogLikelihood = -226. (c) Graph with comparison

of predicted low temperature thermochronological results versus measured ones. (d) Tectonic map where all the samples that were used for dating are plotted.

Fig. 15. Paleogeographic restoration of the Rif during: (a) the Upper Eocene-Lower Oligocene (40-30 Ma), showing the expected location of the subduction of the North African margin and the initial position of the Senhadja Nappe, south of the Ketama Unit; (b) the Lower Miocene (20-15 Ma), showing the translation of the Senhadja Nappe and the development of important crustal stacking; (c) the Upper Miocene (13-8 Ma). Corresponding to the arrival of the Alboran Domain and the emplacement of the Higher Nappes. (a'), (b') and (c') correspond to paleogeographic restoration of the West Mediterranean (modified after Leprêtre et al., 2018).

Fig. 16. Tectonic chart of the External Rif since the Paleocene. The main events areindicated and represented by schematic cross-sections at each stage (see location of each section on Figures 15 a, b and c). The successive tectonic events are correlated with thermochronological data from both the literature (Ketama Unit and Temsamane Unit) and this study (Senhadja Nappe). Three temperature curves are proposed from this data.

Table 1. Interpretation of the Mesorif Tectonic Windows and the Senhadja Nappes of this study, compared to previous interpretations. The new categorization is based on the structural position and stratigraphy of each unit.

THIS STUDY				PREVIOUS STUDIES
MESORIF	MESORIF TECTONIC WINDOWS	NON METAMORPHIC TECTONIC WINDOWS	TAMDA W.	- Tectonic window (Marçais, 1960-1962; Leblanc, 1979)
			North J.KOUINE-M'SILA TECTONIC WINDOW South	- Bou Haddoud Nappe [between Aknoul and Senhadja] (Leblanc, 1979)
				- Senhadja Nappe (Vidal, 1977) - Internal Prerif (Suter, 1965)
			AZROU AKCHAR	- Senhadja Nappe (Leblanc, 1979) - Tectonic Window (Frizon de Lamotte, 1985; Frizon de Lamotte, 1987b)
			JEBEL MERZOUK	- Senhadja Nappe (Favre, 1992)
		TEMSAMANE	RAS AFRAOU TRES FORCAS	- Element of the Alboran Domain (Durand-Delga et al., 1960-62; Suter, 1980) - Temsamane units (Frizon de Lamotte, 1985; Negro et al., 2008)
	SENHADJA NAPPES	METAMORPHIC SENHADJA	KHEBABA	- Element of the Alboran Domain (Durand-Delga et al., 1960-62; Suter, 1980) - Temsamane "semi-klippe" (Booth-Rea et al., 2012) - Senhadja Nappe (Frizon de Lamotte, 1985; Leblanc, 1989)
			JEBEL BAÏO	- Block of Nekor Mega-Breccia (Andrieux, 1971)
		SENHADJA S.S.		- Tortonian olistostrome "Melange" (Vidal, 1977) - Senhadja Nappe (Marçais, 1960-1962 ; Leblanc, 1977)

Table 2. Results of low-temperature thermochronology on Apatite of the Bou Adel and Jebel Baïo gabbros.

Low-temperature thermochronology on apatite

	Sample	Rock-type	Location	grain number	ρ_s (10^5.cm^{-2}) *Ns*	ρ_i (10^5.cm^{-2}) *Ni*	ρ_d (10^5.cm^{-2}) *Nd*	P (χ^2) %	Central age (Ma) ± 1σ	U (ppm)	MTL (µm) ± se	Std dev.	Dpar (µm)
Bou Adel	RE27	gabbro	34°32'08"N 4°29'44"W	26	0.065	0.39	6.73	82.4	17 ± 2	2.3	-	-	2.6 ± 0.4
					97	*583*	*6396*		*26*		-	-	
Jebel Baïo	RE47	gabbro	34°47'37.86"N 4° 0'15.50"W	-	-	-	-	-	-	-	-	-	-

	Name	Rs (µm)	Weight (µg)	FT	4He (nmol/g)	U (ppm)	Th (ppm)	Sm (ppm)	Th/U	eU (ppm)	raw Age (Ma)	Age c. (Ma)*	Standard dev.
Bou Adel	RE27-A	57.9	6.3	0.755	0.8	18.9	75.7	279.5	4.1	39.3	4	6	0.3
	RE27-B	60.9	5.2	0.768	1.6	22.8	86.8	285.1	3.9	45.9	7	9	0.5
	RE27-C	85.7	26.9	0.832	0.5	10.8	24.7	181.9	2.3	18.2	5	7	0.4
	RE27-E	50.9	3.5	0.725	0.8	19.9	63.9	244.9	3.3	37.2	4	6	0.3
	RE27-G	70.8	12.8	0.798	0.6	3.7	13.2	163.6	3.7	8.2	17	25	1.5
	RE27-H	79.3	15.0	0.819	0.5	11.4	27	103.6	2.4	18.7	5	7	0.4
	RE27-I	73.5	15.3	0.806	0.7	10.6	6.6	112.3	0.6	13	11	16	1
Jebel Baïo	RE47-A	42.6	1.9	0.678	1.9	25.4	270	233.2	10.9	92.1	4	5	0.3
	RE47-B	48.8	4.2	0.714	0.4	7.8	45.9	104.7	6.1	19.6	4	5	0.3
	RE47-C	52.8	5.0	0.734	6.4	14.1	147.5	170.7	10.7	50.9	24	29	1.6
	RE47-D	42.1	2.3	0.669	0.7	5.5	34.6	115.2	6.4	14.7	9	12	0.8
	RE47-E	49.6	5.4	0.717	0.2	3.2	12	69	3.8	6.6	8	10	0.7
	RE47-G	44.5	2.9	0.686	0.9	12.3	43.3	28.6	3.6	22.9	8	10	0.6
	RE47	58.3	5.8	0.75	0.5	6.9	31.7	103.5	4.7	15.3	6	7	0.4

7-H			6									
RE4			0.69			242.		11.				
7-I	46	2.8	7	2.7	22.5	6	226.1	1	82.5	6	8	0.4

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Figure 10

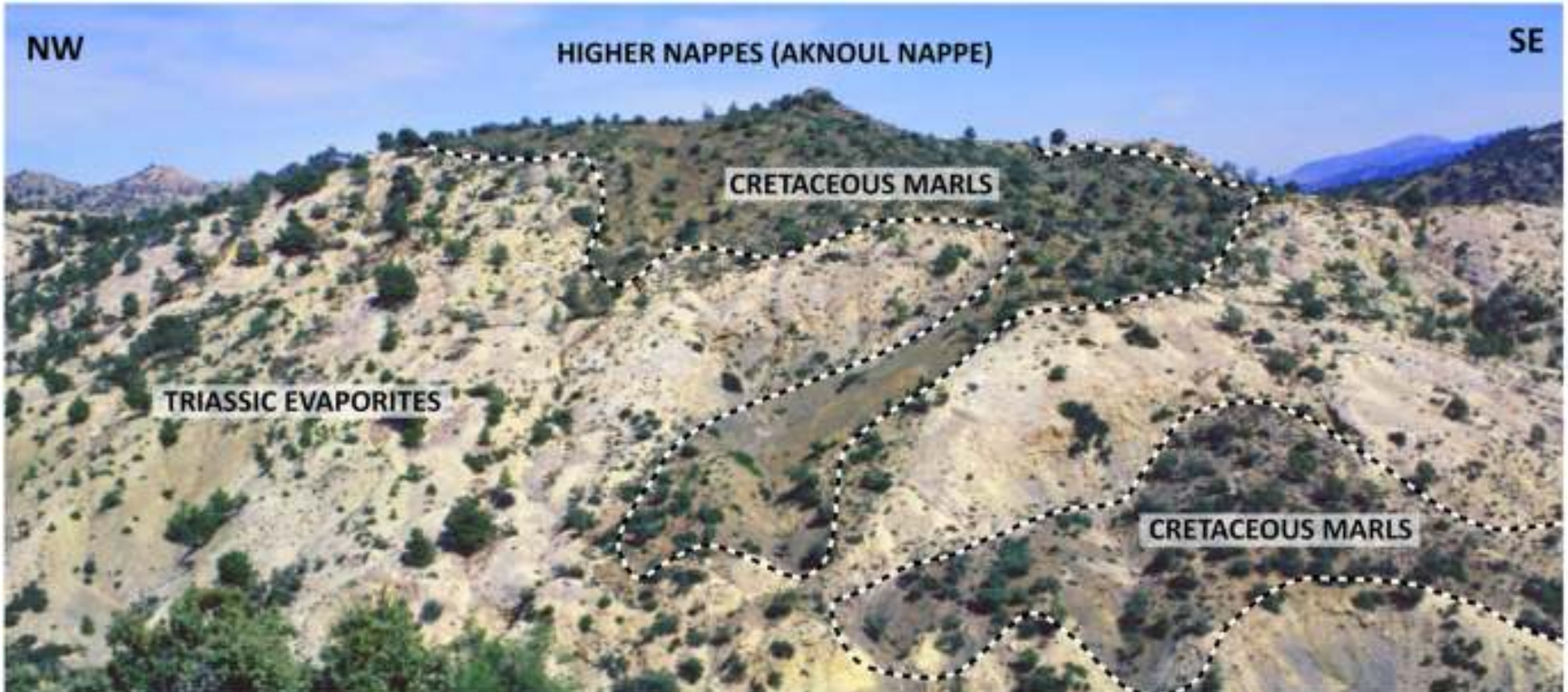
NW
HIGHER NAPPES (AKNOUL NAPPE)
SE
CRETACEOUS MARLS
TRIASSIC EVAPORITES
CRETACEOUS MARLS

Figure 12

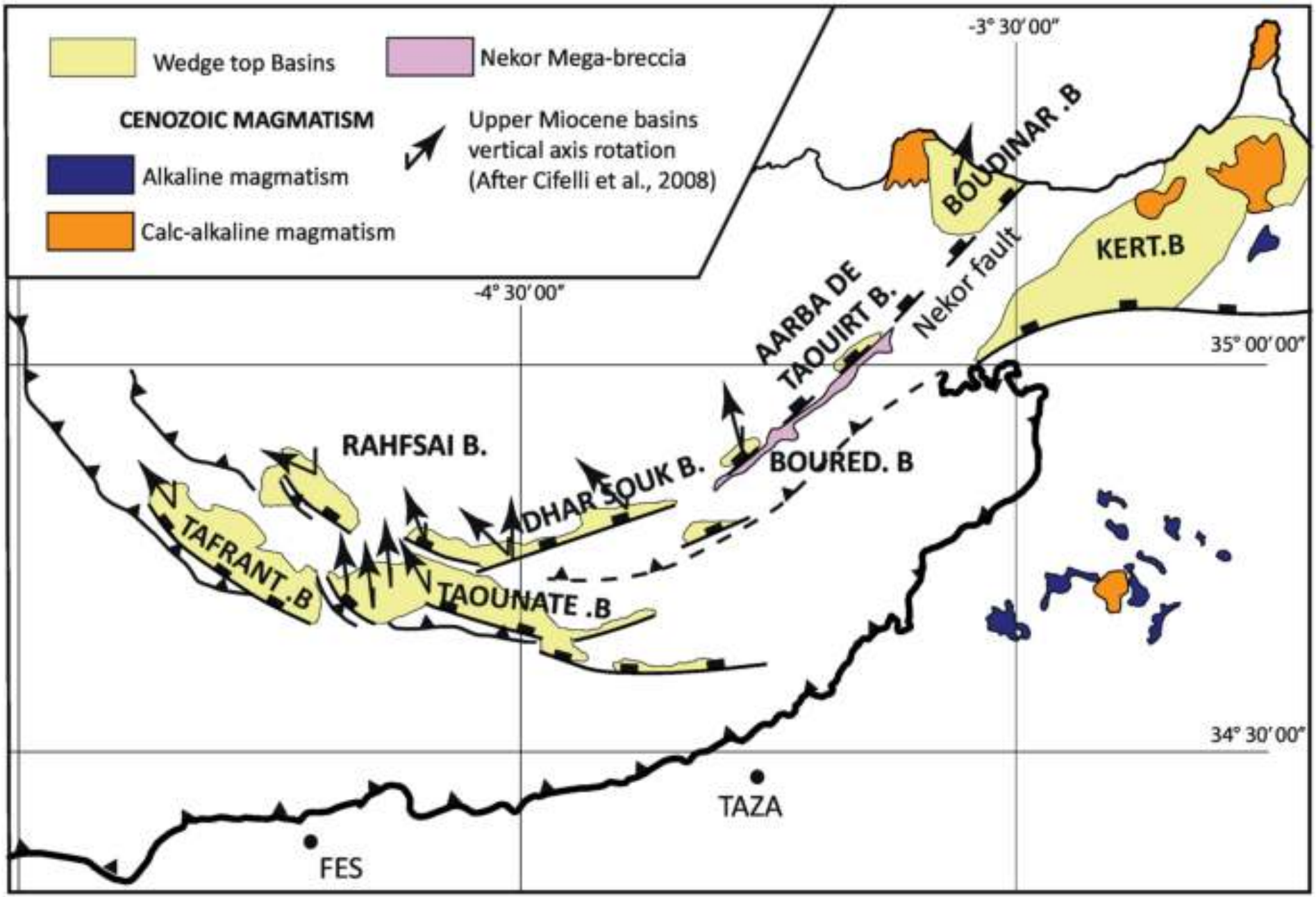
Wedge top Basins
Nekor Mega-breccia
CENOZOIC MAGMATISM
Upper Miocene basins
vertical axis rotation
(After Cifelli et al., 2008)
Alkaline magmatism
Calc-alkaline magmatism
-3° 30' 00"
-4° 30' 00"
35° 00' 00"
34° 30' 00"
BOUDINAR .B
KERT.B
Nekor fault
AARBA DE
TAOUIRT B.
RAHFSAI B.
DHAR SOUK B.
BOURED. B
TAFRANT .B
TAOUNATE .B
TAZA
FES

Figure 13